THE EFFECT OF COLD WORK FOLLOWED BY ANNEALING UPON THE PHYSICAL PROPERTIES OF 0.22% CARBON-0.89% MANGANESE STEEL

BY

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ERRATA

On Page 18, line 13, "deformel" should read "deformed."
On Page 20, "Figure 34" should read "Figure 39."
On Page 25, bottom line is upside down.
On Page 26, line 5 is upside down.
Footnote on page 36 should be on page 35.
On Page 36, line 31, "Detected" should be "Accepted."

PREFACE

The structural field today constantly encounters numerous problems. In certain cases these problems are of minor importance, in others they involve life and death. An engineer is always on the alert to prevent failure of structural parts, especially parts which are the links for important structural members. With the advent of the oxyacetylene torch in this field, brackets shaped by such a flame have been found to fail. As the true cause for such failures was apparently unknown, various technical institutions were stimulated to seek a solution of the problem.

The Testing Laboratories of the Department of Civil Engineering, Columbia University, have concentrated considerable effort on the solution of this problem. Professor Albin H. Beyer, Director of Testing, and Assistant Professor William J. Krefeld, Engineer of Tests, were both particularly interested. It was Professor Beyer who first saw the importance of investigating this problem, which was later carried out in detail by Professor Krefeld. The author is deeply indebted to both of these men for their helpful suggestions, as well as for the use of the laboratory and equipment during part of this research. Mr. Julius Boldtman, photographer for the Testing Laboratories, also aided the author materially with his knowledge of photographic effects and assistance.

Sincere thanks are due Mr. Evan Ward of the Russell, Burdsell and Ward Nut and Bolt Company of Portchester, New York, who furnished the steel used in this research.

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Finally, the author wishes to take this opportunity of expressing his sincere gratitude to and esteem for Professor William Campbell of the Department of Metallurgy, Columbia University. It was Doctor Campbell's constant encouragement and urge for better things which made this volume possible.

ROBERT L. GERUSO.

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INTRODUCTION

When steel, especially low carbon steel, is cold worked, the grains are distorted and elongated in the direction of working. Such treatment causes slippage in the grains which is revealed structurally by "Slip bands" and "Slip lines," the former being entities in a single grain sliding past each other, and the latter being traces of crystallographic planes. The physical properties are also affected; the tensile strength and hardness are increased with a corresponding decrease in ductility. The effect of cold working on the ability of steel to resist shock is not definitely known; as a matter of fact it is a subject of considerable research. The industry has experienced many failures of steel chains from shock although static tension tests made of the broken parts showed normal properties.

In general heating cold worked material below the recrystallization temperature produces a slight increase in strength and hardness. The ductility, however, remains practically unchanged until the equi-axing temperature is reached. This equi-axing temperature, which varies for different metals, is the temperature at which the cohesion of the amorphous modification is equal to that of the crystalline. At this point, there is a sharp drop in strength and hardness, with an equally marked increase in ductility (ability to flow as well as to absorb shock without fracturing.) As the material is heated above this equi-axing point, the grains become coarser; therefore there is very little change in physical properties with the exception of lowered shock resistance.

In the case of steels in general, and low carbon steels in particular, a new factor becomes apparent, namely the transformation of alpha iron into gamma iron and the consequent solubility of carbon. When steel is heated to Ac3, nuclei for new grains appear and the size and number of these grains will depend on the time this steel is held at, or slightly above Ac3. Slow gradual transformation from alpha to gamma iron followed by slow cooling produces large grains, whereas rapid transformation followed by rapid cooling develops small grains. Coarse grain structure in metals is undesirable as this condition decreases the resistance to shock.

Recently, an old problem has been studied in the light of modern knowledge, that is, Stead's Brittleness; we now call it brittleness due to abnormal grain growth.

Another problem still unsolved is brittleness in the "blue" or a brittle condition brought about in low carbon steels by working them at a blue heat (approximately 300° C.), or by heating cold worked steels to the temperature at which the outer skin turned blue. The temperature at which this blue color of steel becomes visible is, of course, different for steels of varying carbon content.

A few explanatory words in regard to our knowledge of ferrous materials in general at a blue heat, and steel in particular, are necessary. French [41] and Tucker [42] summarized in 1924 the existing information regarding the mechanical properties of steels at elevated temperatures, especially in the blue heat range.* The former investigator[41] concluded for fire box steel that the elastic limit can be made to approximate the ultimate strength by overstraining successively at blue heat with gradually increasing load. Moreover, a marked degree of brittleness was observed.

This latter property, a state of least plasticity, in the blue heat range (315-370° C.) (600-700° F.) was previously mentioned by Risdale.[46] He reported that whenever soft steel is worked and soaked in a furnace within the above mentioned temperature range, the steel developed brittleness. Fettweiss,[10] Fremont,[40] Korber and Dryer,[44] Mauer and Maitlander,[26] and Preuss[45] also found that steels worked in this "Blue Heat Range" developed a pronounced brittleness.

Results somewhat similar to those found by French on mild steel were recorded by Jeffries[43] in his study of the physical properties of Armco iron. He determined that whenever iron was cold drawn a moderate amount, its tensile strength was lower than when tested at a blue heat (200-300° C.). However, when the deformation was excessive, (96% or more), the tensile strength was greater at room than at higher temperatures. Brittleness in Armco iron was obseved by Jeffries as well as by other investigators.

Although various explanations have been offered from time to time to account for this brittleness at blue heat, at present none appear to be entirely satisfactory.

Fettweiss[10] pointed out that elastic recovery after overstrain occurred at a blue heat and further stated that in the explanation for this phenomenon would be found the cause for brittleness at blue heat.

*Blue Heat Range means within a temperature range at which the material attained a blue color.

Mauer and Maitlander[61] attributed the brittleness developed in mild steel when worked in the blue heat range to the solubility of carbon in iron. Jeffries[50], on the other hand, stated that perhaps this abnormality was due to an undetermined critical point in iron. In a discussion of Jeffries' paper on "Physical Changes in Iron and Steel Below the Critical Range" Archer stated it was due not so much to an undetermined critical point as to an increased resistance to motion on the slip plane formed during deformation.

An entirely different view was suggested by Fry[49]. After the discovery of his reagent for revealing strain lines in deformed steels, he decided that these markings were the answer to "Blue Brittleness." As a basis for this conclusion he pointed out the coincidence between these strain lines and the temperature to which the deformed steel must be heated (blue heat range) to bring them out.

Dean[46] and his associates state:

> "We come now to the conclusion that commercial irons owe their properties of hardening by reheating after cold work as well as their increase in tensile strength in the range 100-300° C., to the solution of small amounts of iron nitrides present."

We may state, therefore, that there are the following known types of brittleness in steel:

1. Brittleness found in steel annealed to about 350° C.
2. Brittleness caused by abnormal grain growth.
3. Brittleness caused by working low carbon steel at a blue heat approximately 300° C.

New problems involving failures which are apparently connected with one of these types of brittleness are constantly arising. For instance, about the middle of July, 1927, a problem which involved the brittleness of steel was submitted to the Columbia University Testing Laboratories. Steel column brackets intended for use in construction had fractured prior to or during erection. Physical tests offered no explanation for this failure. As a matter of fact, the results obtained in these tests (ultimate strength, elongation, reduction of area, as well as Brinell hardness) compared favorably with the physical properties of a good grade of structural steel. The fact remained, however, that failures had occurred and an investigation of the causes of this failure was undertaken by Professor Krefeld[79] of the Columbia University Testing Laboratories.

In a similar manner, in order to explain the unaccountable brittleness of low carbon steel this investigation was undertaken.

GENERAL STATEMENT OF THE PROBLEM

The major problem was to determine, first, the effect of cold working followed by annealing below the normal transformation range upon the physical properties of 0.22% carbon—0.89% manganese steel. In the second place, it was necessary to determine whether tensile test results interpreted in the light of other confirmatory physical tests would be sufficient to indicate brittleness in normally tough steel. Finally, an attempt was made to apply the conclusions reached from the above tests in solving certain failures occurring in the structural steel industry.

Specific Problem

Specifically, however, the problem may be divided into three parts:

1. A study of the effect of annealing at temperatures ranging from 0° to 600° C., on the physical properties (from Tension, Rockwell, Bend and Impact Tests) of 0.22% C.—0.89% Mn. steel, cold worked 0, 4, 6, 8, 12, 16, and 20%.
2. A study of the tension test to determine if it reveals brittleness in a normally tough steel which had been cold worked followed by low temperature annealing.
3. A study of the variables involved in the fabrication of structural brackets in order to account for certain failures which have occurred in practice.

REVIEW OF LITERATURE

Many investigators have worked with iron or steel which had been cold worked varying degrees followed by heat treatments at low temperatures.

As early as 1886, Bauschinger[6] studied the influence of aging and, to a slight extent, the effect of tempering on the physical properties of cold worked mild steel.

Muir[28], in 1900, who also worked with mild steel, studied the influence of tempering in boiling water, as well as cold stretching, on the magnetic hysteresis of such steel.

In 1907, a paper by Stromeyer[35] caused a great deal of apprehension among manufacturers of mild steel boiler plate. Continued

observation led him to believe that mild steel, especially that which was sheared and aged, exhibited a marked brittleness. Moreover, this brittleness was increased by bending at a blue heat. He cited instances where mild steel boiler plate failed in service. After thorough examination, this phenomenon was attributed to overstrain in compression, such as cold riveting followed by an aging period at low temperature. Stromeyer's tests showed that both aging and tempering affected the brittleness of mild steel, especially if it had been previously overstrained.

Goerens[13] in 1911, using mild steel (C. 0.08, Si. 0.08, P. 0.059, and Mn. 0.39%) in the form of wires which were reduced 85% by cold drawing, investigated the influence of thermal treatment on cold worked steels. The curves in Figures 1 and 2 show the result of his research. It is apparent that the effect of annealing below 520° C., is negligible. At 520° C., however, a sudden reversion of the metal to its original state occurred. From experiments on other mild steels, Goerens stated that the critical temperature at which this sudden change in physical properties took place varied for different kinds of mild steel, although he did state that the critical temperature ranges from 520° to 580° C. These curves do not reveal any loss in toughness at about 300° C.; on the contrary, they show an increase.

Baumann[5] has summarized a series of investigations performed in Germany on the brittleness developed in mild steel caused by heating plates previously overstrained in compression.

"1. There are certain mild steels which, when subjected to heavy compression followed by heating to a yellow temper, develop decided brittleness on subsequent cooling. Many a break or incipient crack can thus be accounted for, especially as heavy squeezing pressures followed by heating occur frequently in practice; for instance, heavy squeezing pressures result from poorly cut threads, forced fits, all kinds of calking, in punching or embossing, in drawing wire, in rolling, in riveting, using heavy pressures, in stamping, etc.

2. Cold bending or cold working is not in general sufficient to induce brittleness in the mild steel. Only mild steel possessing certain properties become brittle, and then only after heating. Test specimens taken from the same plate

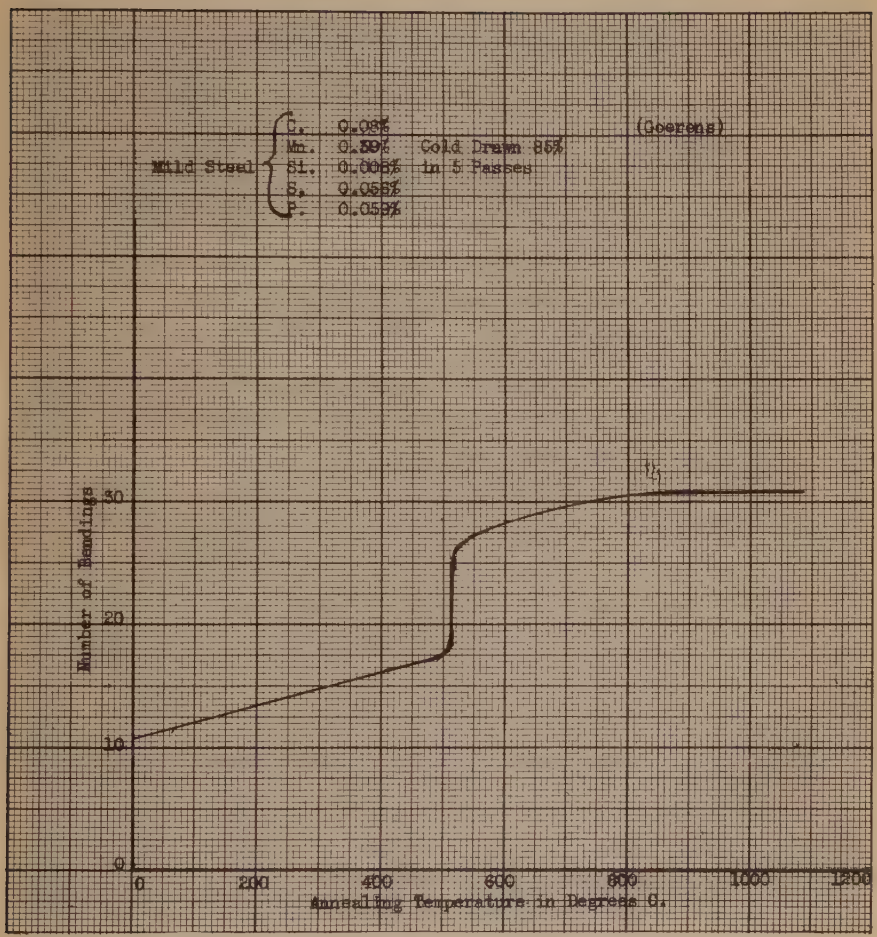


Figure 1 Number of Bendings to Failure of Mild Steel Cold Drawn 85% and Annealed, Tested at Room Temperature

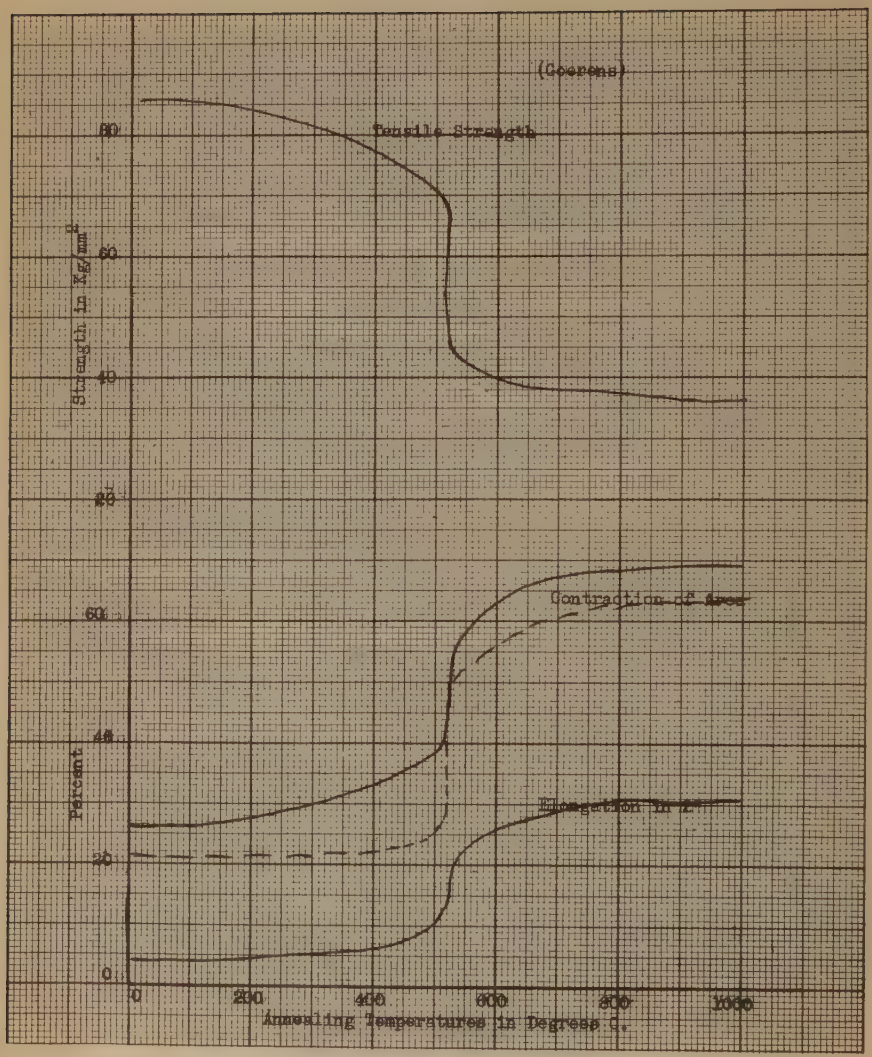


Figure 2 Tensile Properties of Cold Drawn Mild Steel Wire

do not always develop the same degree of brittleness. The well established rule that sharp, reentrant angles, or turned grooves be avoided as far as possible is not affected by the tests herein described.

3. A method of testing boiler plate is described which when applied to several plates which had developed cracks in practice showed the metal in these plates to be inferior although it had withstood satisfactorily the tests* usually applied to such material. This test consisted in pressing a hardened steel cylinder ten mm. in diameter against a specimen of the plate taken perpendicular to the direction of rolling and with the axis of the cylinder inclined 60° to the axis of the specimen. A load of 250 to 300 kg. per centimeter length of impression was used. The thickness of the test section in the direction of rolling was 15 mm. The test specimen was then heated to a yellow temper color, and after cooling in water was subjected to a bending test.
4. The tests made included plates up to 20 mm. (0.787 in.) in thickness and a tensile strength of 4100 kg. per sq. cm. (58,300 lb. per sq. in.).
5. The effect of the direction of rolling was quite pronounced. This had also been observed in notched impact tests. The metal is tougher in the direction of rolling than at right angles thereto.
6. The tests described appear to offer a solution to the problem of distinguishing between good and inferior mild steel plates and in a certain sense they constitute an amplification of the tests now in use. The sensitiveness of mild steel to the treatment described above can, of course, be determined by other methods; for instance, compressing the plates until the yield point has been exceeded, heating, cooling, and finally subjecting the material to a notch impact test.

In 1916, however, Bauer,[3, 4] using mild steel (C. 0.29%, Si. 0.08%, Mn. 0.98%, P. 0.031%, S. 0.048%, Cu. 0.06%, and Cr. 0.015%) which had been cold drawn to a reduction in diameter of approximately 12%, obtained the curves in Figure 3. An analy-

*Tensile Tests.

sis of these curves shows that although static tensile strength of the material increased, reaching a maximum between the temperatures of 300 and 400° C., the impact resistance, or dynamic testing strength, decreased within these same ranges of temperature. The ductility, on the other hand, was not affected until a temperature of 300° C. was reached, when a decided rise occurred.

A similar phenomenon was found by Matsuda[25] in testing cold drawn carbon steel, namely that the tensile strength was increased by annealing at low temperatures. Matsuda, however, obtained a maximum tensile strength for previously cold drawn steel by annealing at 200° C., which temperature is much lower than that determined by Bauer. Since this temperature coincides with the magnetic transformation of cementite, the author attributes the extra strength to this change.

Heyn[15], in 1917, in his paper on "Internal Stresses in Cold Worked Material" stated that steels, worked either at room temperature or at blue heat, may have the value of their elastic limit and yield point altered by subsequent low temperature annealing.

In determining the effect of high riveting pressures upon the embrittlement of boiler plates, Doctor Wolfe[38] in 1917 found that low temperature annealing was very important in causing failure. He also showed that the result of tensile tests of this steel (C. 014%, Mn 0.451, S. 0.047, P. 0.136, As. 0.117, S 0.028%) was that of normal material. Impact tests, however, showed that it required only 20 to 40 blows to break the deformed material, whereas normal steel required 70. Investigation showed that failure occurred more frequently at the edges where the material has been subjected to high riveting pressures, and where a pronounced brittleness was found. In a discussion of this paper, Milton also related similar observances in his experience with boiler plate material.

Bauer[4], again, in 1918, demonstrated by notched bar impact tests, that boiler plate material made of mild steel (.12% C.), severely cold working by compression (the usual practice in calking rivets) followed by annealing below the critical range has its toughness appreciably lowered. The curves in Figure 4 show that the impact toughness of boiler plate material attains its minimum value when annealed at 250° C. to 300° C. resulting in a reduction of 39% in comparison to the unannealed material.

The work originally undertaken by Bauschinger and Muir,

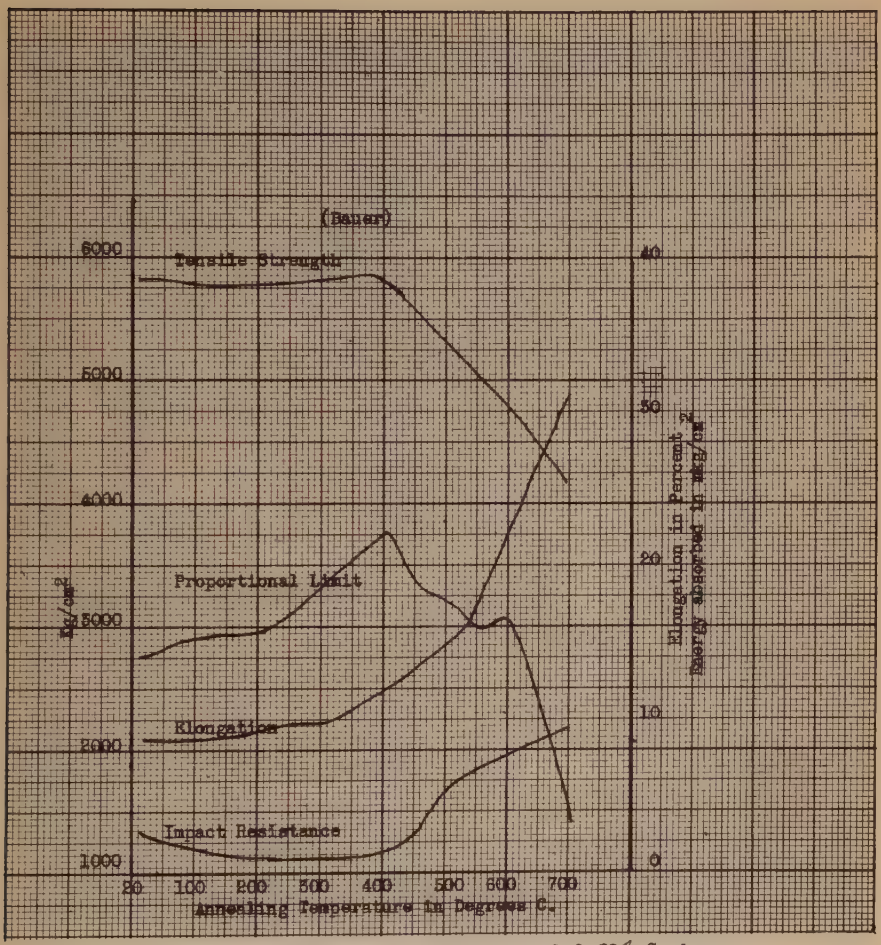


Figure 3 Physical Properties of 0.29% Carbon Steel Reduced in Diameter Approximately 12% by Cold Stretching prior to Annealing.

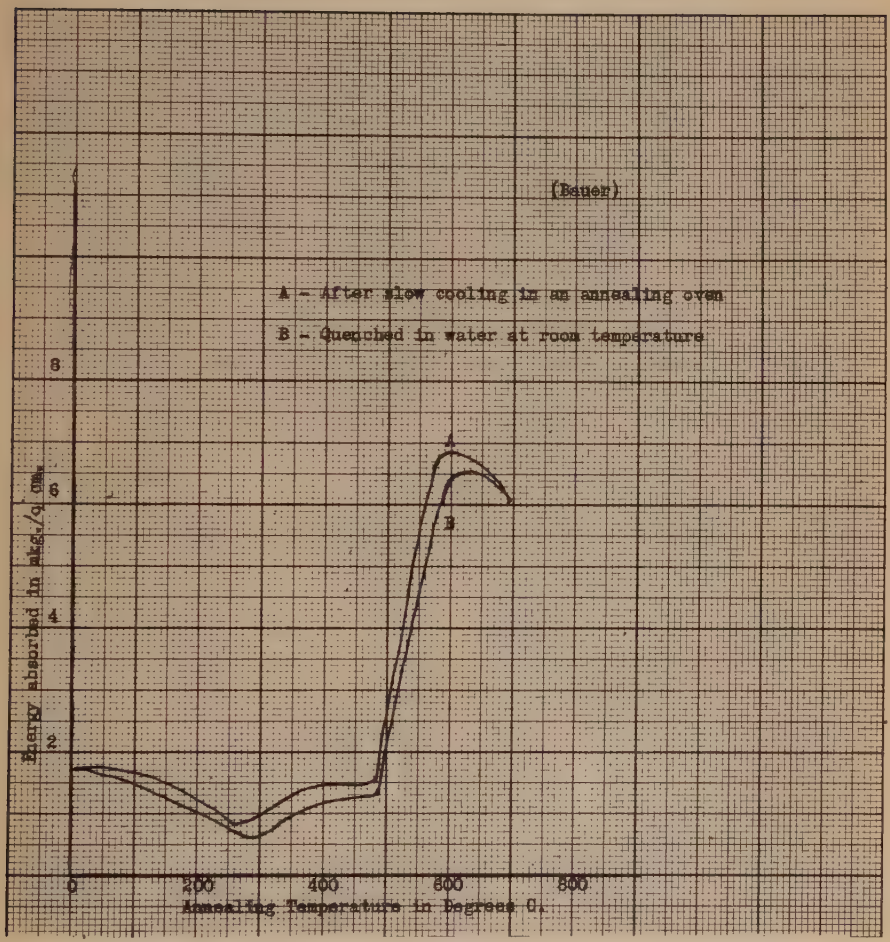


Figure 4 Boiler Plate, Pressed Cold and Annealed

was further extended by Van den Broek[37] in 1918 when he studied the effect of cold working on the elastic properties of mild steel (0.16%, 0.21%, 0.26%, and 0.95% carbon content). The results obtained were as follows:

"1. When mild steel is cold worked and properly aged or tempered and subtested in the same sense* as that of cold working, its elastic limit may be raised more than 100% and from 10 to 20% beyond the stress at which cold working was discontinued.

2. When mild steel is cold worked in one direction and properly aged or tempered, but tested in either one of two senses of a different direction, then its elastic limit may be raised some 50%.

3. When mild steel is cold worked in one sense and properly aged or tempered but tested in the opposite sense, then the elastic limit remains at the value of the original elastic limit, but the yield point is raised.

4. Tempering cold worked steel at temperatures from 100 to 300° C., or aging cold worked steel has a tendency to perfect its elastic properties. Tempering merely accelerates the effect of time."

Following the line of research of previous German investigators, Fettweiss[10] in 1919 concluded that by working steels below 500° C. the material is brought to a condition under which aging occurs. The aging, which is analogous to additional cold working, attains its full value only after months and years at ordinary temperatures, but with higher temperatures, the process proceeds with much greater rapidity, until the period for its completion is finally reduced to a fraction of a second. This caused the condition known as "brittleness" at blue heat. Steel which had been worked at room temperature, annealed below the critical range and then tested, also exhibited the property of blue brittleness. Experiments made later in conjunction with Martens also verified the above conclusions.

Adams[1] studied the effect of heat treatment after cold work on hypo-eutectoid and hyper-eutectoid steels of the following composition, before being cold worked 35 and 48% respectively:

*The author used this term to express the direction of cold work and testing; that is if the cold working was performed in a longitudinal direction, the tests were likewise performed in the same direction.

35% Reduction: C. 0.48, Si. 0.17, Mn. 0.68, S. 0.047, P. 0.025
48% " C. 0.42, Si. 0.17, Mn. 0.73, S. 0.033, P. 0.029

In 1920 he reached the following conclusions:

"1. Any form of heat treatment after cold working below the recrystallizing temperature (500-600° C.) according to the class of steel has, on the whole, a deleterious effect on the physical properties.

2. Although the elasticity and percentage of elongation of the material are increased by such treatment, the bend and torsion tests, however, show that the steel is in a brittle condition. (Figure 5.)

3. Time plays a very important part in this treatment and such operations as hot galvanizing and tinning should be conducted as quickly as possible, so that the effects of heating are reduced to a minimum.

4. The low elastic limit in cold worked steel indicates the presence of a mobile condition, and supports the amorphous cement theory of cold work.

5. The recovery of elasticity accompanied by increased brittleness after heat-treatment, and, to a slight extent, after aging, supports the idea that the amorphous cement is unstable, passing from a viscous condition to a hard glassy or vitreous condition, and finally returning to a certain temperature to the crystalline condition.

6. The structural effects of heat treatment after cold-work are scarcely visible until recrystallization commences. When this occurs, the ferrite forms new grain boundaries and cementite collects in the form of nodules, which tend to coalesce."

In a paper on "The Effect of Temperature on the Behavior of Iron and Steel in the Notched-bar Impact Test," in 1925, Greaves and Jones state: "The impact figure of iron and steel at atmospheric temperature is reduced by cold work and still further reduced by a low temperature heat treatment following cold work." This, however, was a review of what they found in 1920.[19] (Figures 6, 7, 8.) Again, while investigating the effect of overstrain on the elastic properties of various carbon steels, Greaves,[19] in 1921, found what had already been determined by past investigators, that a recovery in the elastic limit occurred by reheating at 100° C., and further increased in value by reheating from 250 to 300° C.

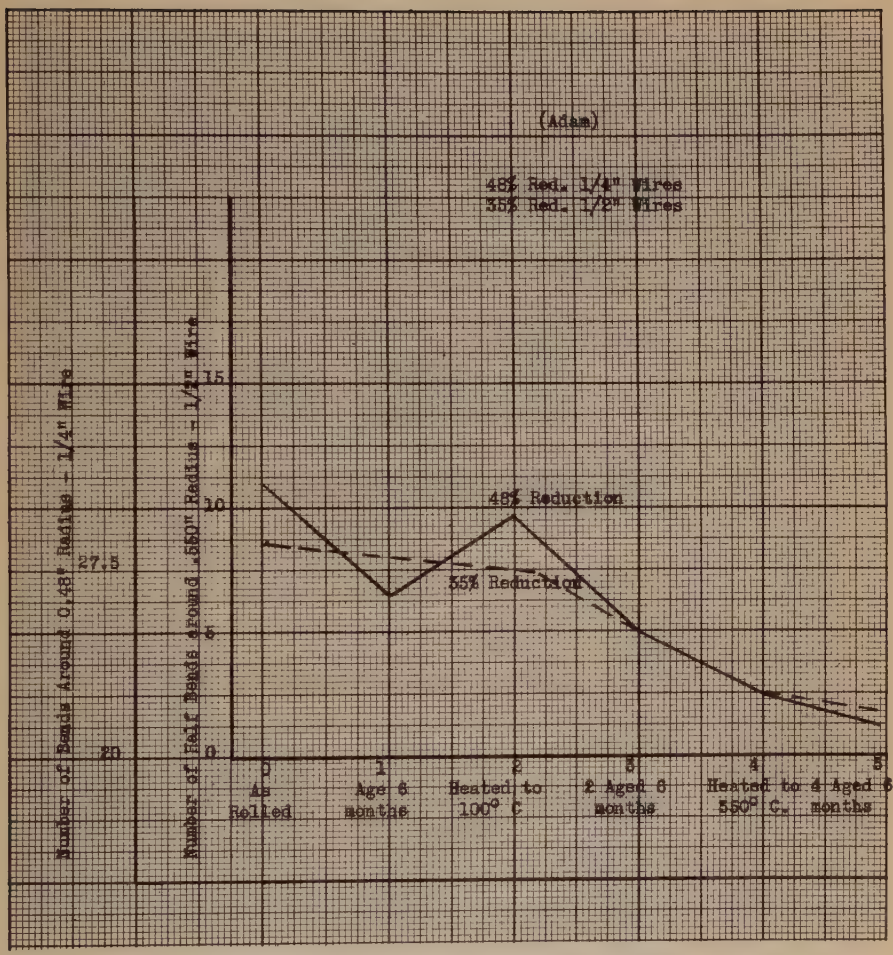


Figure 5 Age Results of Bend Tests on Streamline Wires Cold Worked 48.0% - 35% Respectively after Heating and Aging.

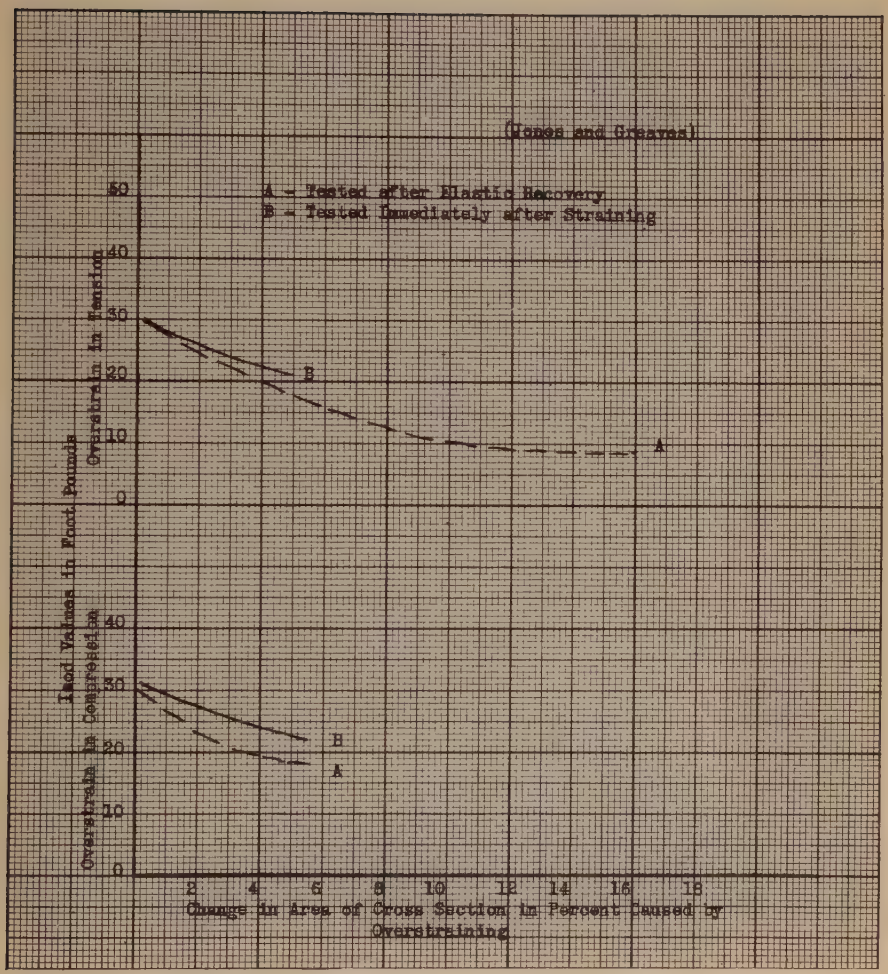


Figure 6 Steel A

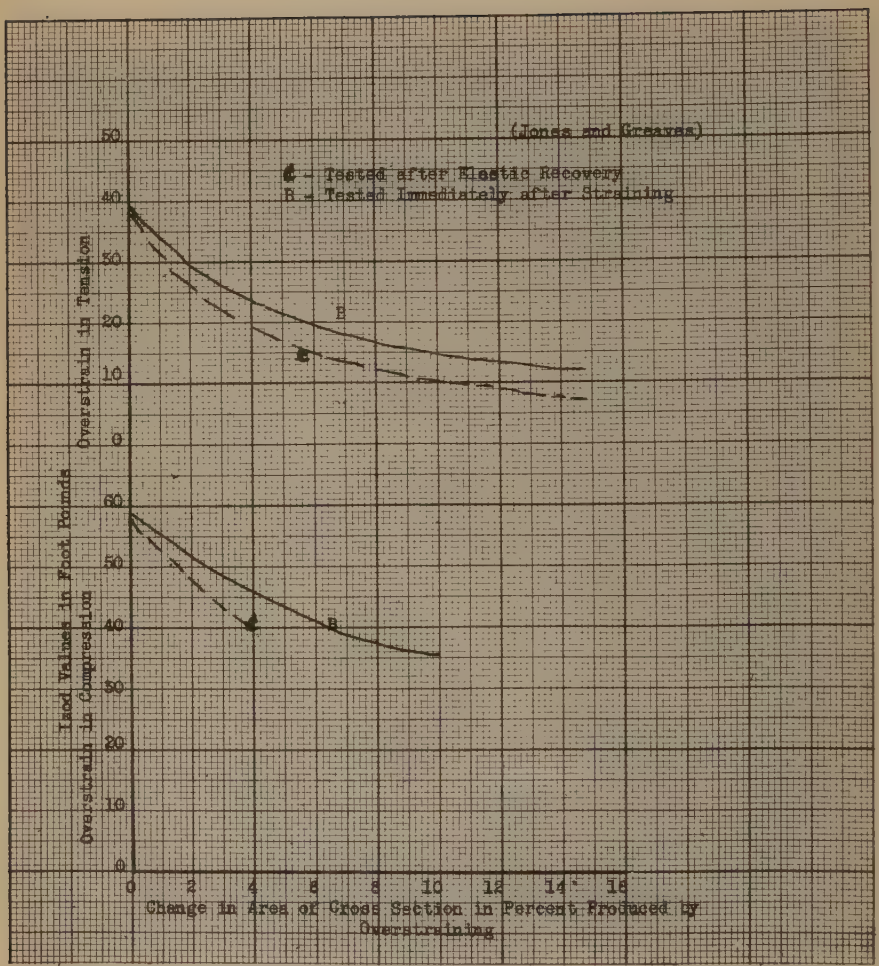


Figure 7 Steels C and B

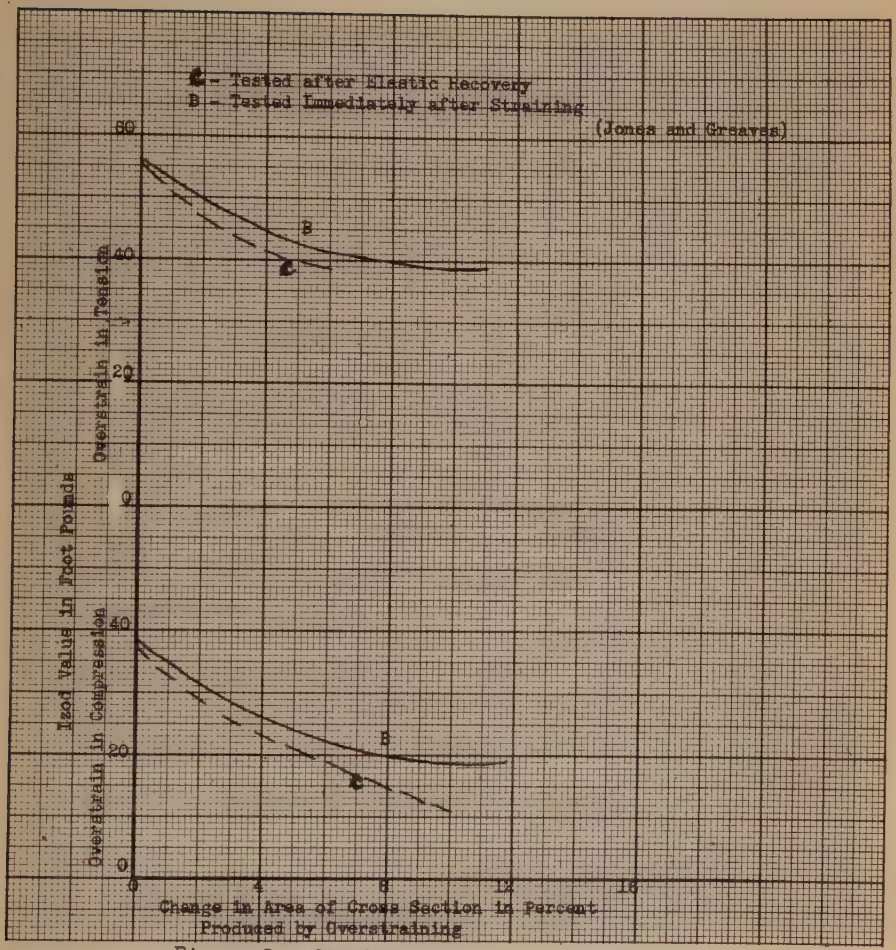


Figure 8 Steels B and C

Pomp[30], in 1921, found that when mild steel (C. 0.05, P. 0.005, Mn 0.10, S. 0.035, Si. Trace, Cu. 0.024%) was deformed in the cold state from 8 to 16% by rolling prior to annealing between 650 and 850° C., it showed a considerable coarsening of grains. The coarsening was found to be most apparent when the cross-section was reduced 11%. This pronounced coarsening of grains also affected the normal physical properties. The surface hardness was lowered 9 to 14% ; the yield point 35 to 47% ; the notched toughness 9 to 25%. The structural change showed that within the range of cold work, pearlite disintegrated and cementite, thus freed, was deposited in the form of fine threads along the ferrite crystal boundaries.

A paper entitled "Blue Brittleness and Aging of Iron" issued in 1921 by Korber and Dryer[23], included the curve shown in Figures 9, 10, 11. The composition of these cold drawn steels were:

	C.	S.	Mn.	P.	S.	Cu.	N.
B	0.21	0.21	0.57	.038	.044	.02	.004
S	0.20	0.21	0.46	.045	.033	.01	.003
K	0.08	0.02	0.07	.001	.002	.04	.007

These curves show that the maximum annealing effect was attained at about 100° C., and that the notched bar impact test revealed very clearly that the toughness of cold stretched specimens was much reduced by annealing at low temperatures.

In 1922, Korber[22], again found that critically worked (10% reduction of area) mild steel (C. .08, P. .01, Si. .02, S. .002, Mn. .07, Cu. .04%) when annealed between 650° C. and Ac3 point, had its mechanical properties altered. As a matter of fact, in consequence of the above conditions, the elastic limit and yield point were lowered one-fourth and one-half respectively from their original values. The tensile strength was likewise reduced but to a less degree, whereas the elongation showed very little change. Moreover, a very important fact was observed. Steel which had been rendered coarsely crystalline by critical cold working and subsequent annealing showed decided brittleness under the notched bar impact tests, whereas static tests failed to show any diminution in its capacity for deformation.

Fisher[11], and Hillman and Coonan[16], in 1923, investigated the effect of cold working steel followed by annealing upon grain size, as well as on some of the physical properties after recrystallization.

The former found that heating for a long time at 200° C., made the steel very brittle while, on the other hand, Hillman and Coonan verified Pomp's conclusion that it was necessary to deform mild steel from 8 to 16% in order to grow the coarsest grains by reheating.

Employing two steels, 0.04% and 0.85% C., deformed 14.8 and 8.1% respectively, prior to annealing at low temperature. Rees[31] in 1923 obtained the curves in Figures 12 and 13. Here the effect of annealing at low temperature on the maximum load and yield point is not appreciable. They do not decrease in value until the material is annealed above 300° C. The elastic limit was in all cases greatly improved by annealing at low temperature. The highest values for the material tested were obtained after annealing at 300° C., which is a confirmation of similar work performed by previous investigators.

In 1925 and 1926, Delbart[7] also found that the tensile properties of cold rolled steels (0.127, 0.4 and 0.6% C.) subsequent to reheating from 400° to 900° C. showed a drop toward a minimum to about 650 to 700° C. These steels were subjected to cold rolling with six passes through the rolls alternating with intermediate reheating at 650 to 700° C., followed by two final passes. The curve for the impact toughness of 0.3% C. steel is shown in Figure 14. A minimum value for toughness, as determined by the Charpy impact test, occurred at 565°.

While investigating the brittleness of mild steel, Mauer and Maitlander[26] in 1925 obtained the results shown in Figure 15. These indicate that the toughness of these steels (boiler plate material and 3.5% nickel steels) was greatly reduced by cold working followed by low temperature annealing. As the tests were made only on samples annealed up to 300° C., the work in this respect is incomplete.

That the hardness of deformed steel is also affected by annealing at low temperature is shown by the curves of Sauveur and Lee Lee,[36] and Ishigaki.[17] (Figures 16 and 17.) Sauveur and Lee used 0.50% C. steel deformed various amounts (per cents not given) prior to heat treatment. A maximum increase in hardness was found at approximately 350° C. Ishigaki determined the hardness of steels (0.1, 0.3, 0.5, 0.7, 0.9, 1.1% C.) at the broken section of tensile specimens after heat treatments. The results of these curves (Figures 16 and 17) show that the cold worked iron and

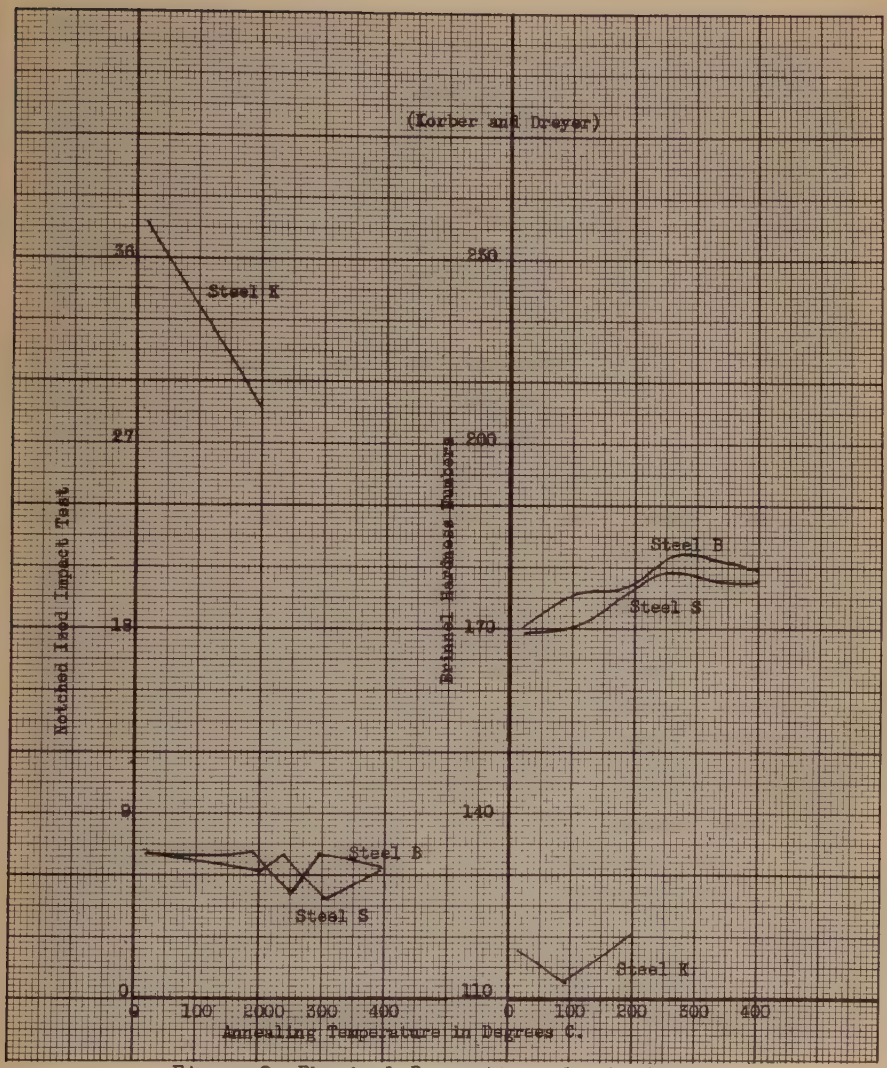


Figure 9 Physical Properties of Mild Steel Cold Drawn Approximately 10% Prior to Annealing.

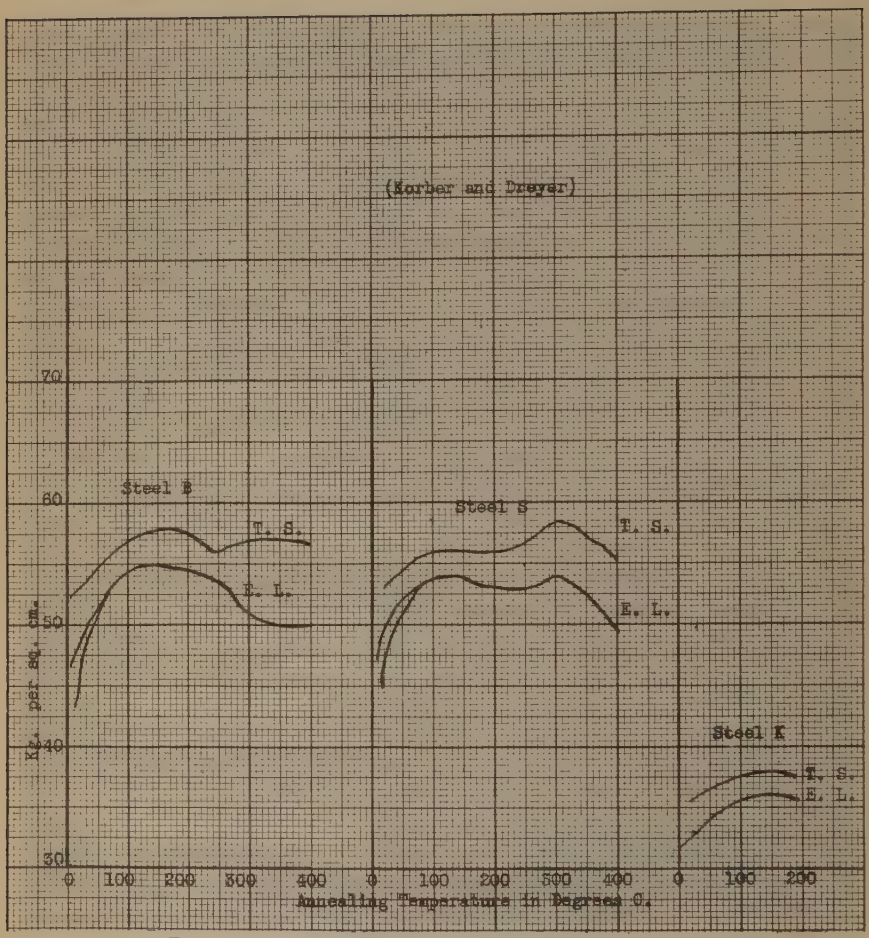


Figure 10 Physical Properties of Mild Steels Cold Drawn Approximately 10% prior to Heating at the Above Temperatures.

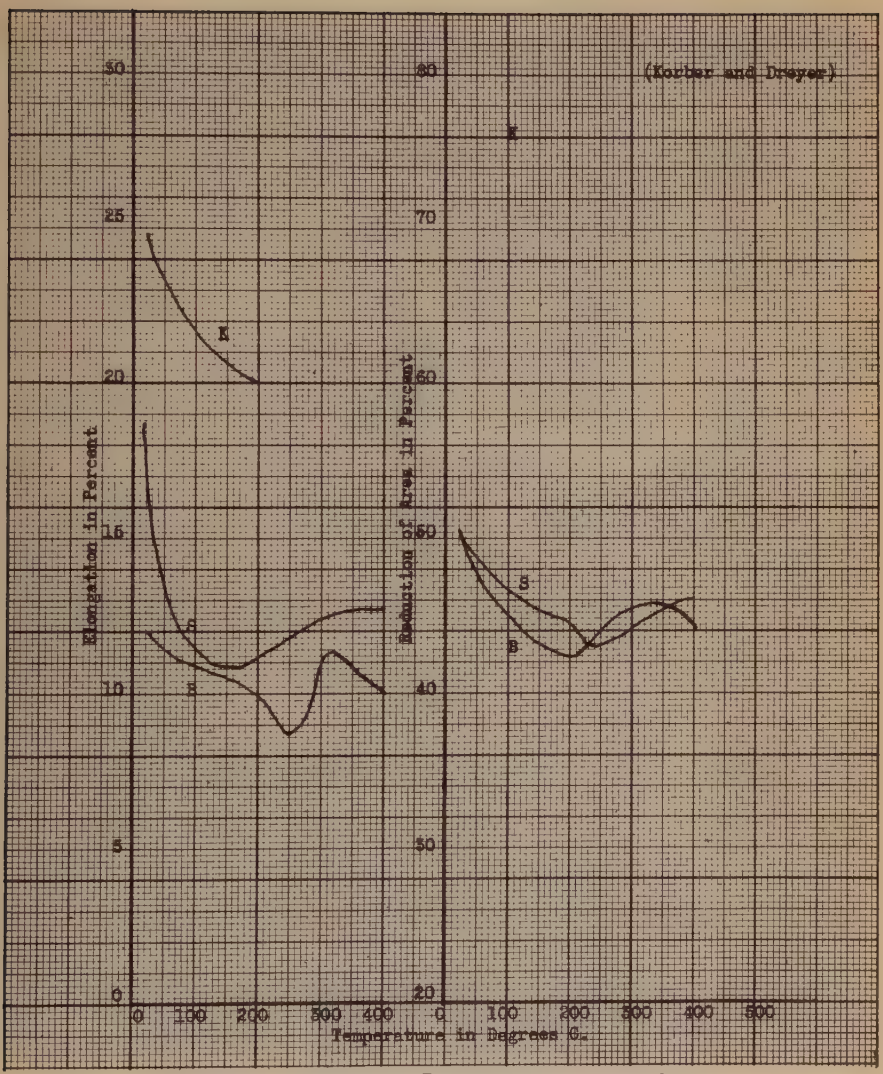


Figure 11 Physical Properties of Mild Steels, Cold Drawn prior to Annealing.

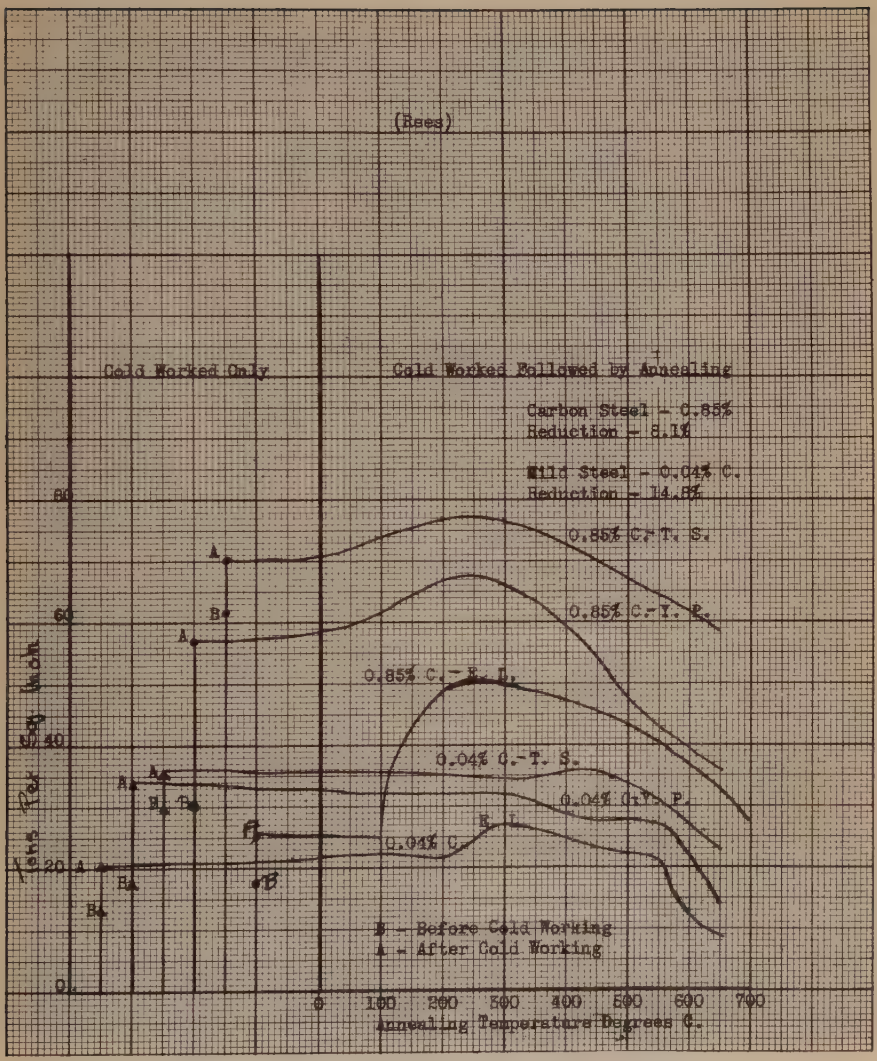


Figure 12 Tensile Tests on 0.85% and 0.04% Carbon Steels.

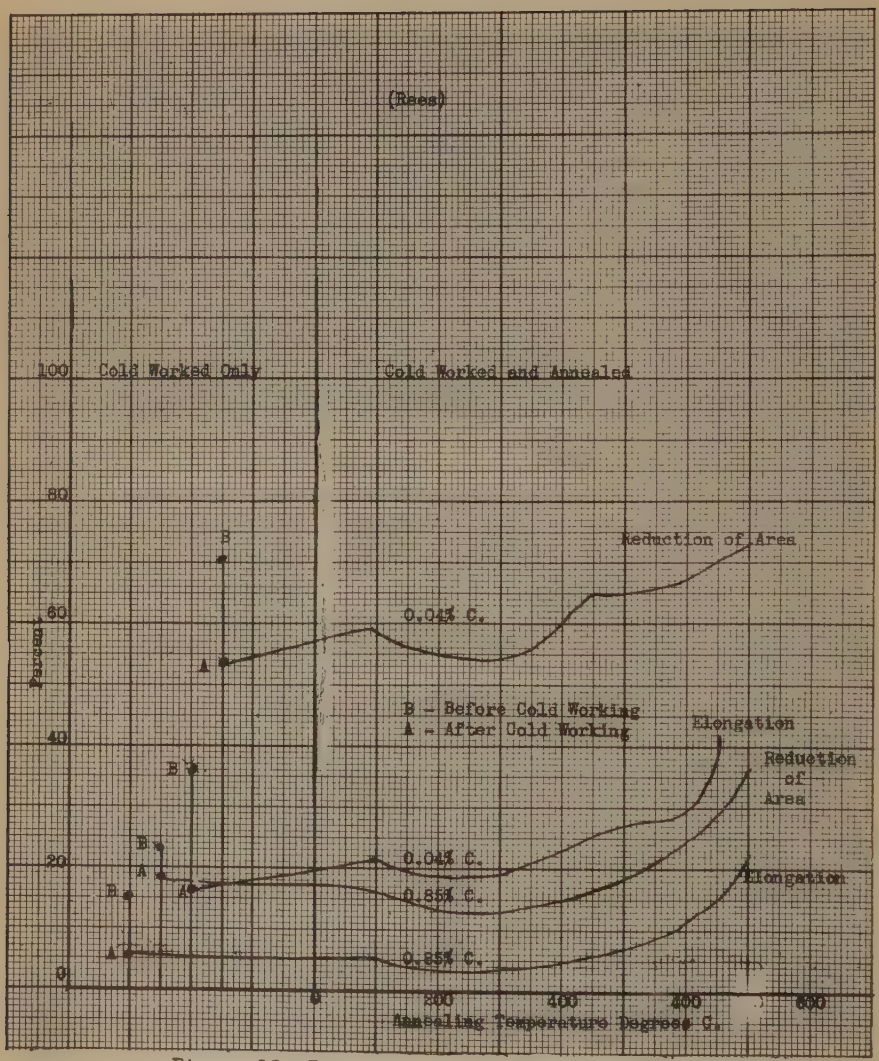


Figure 13 Tensile Tests on 0.04% and 0.85% Carbon Steels.

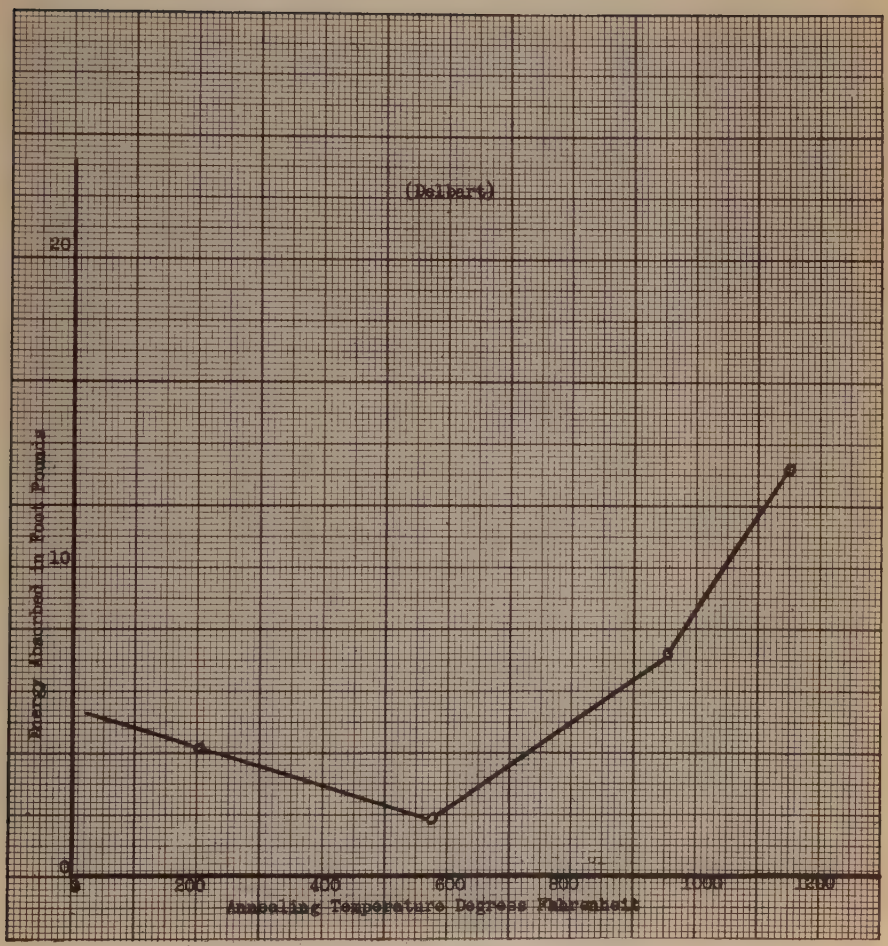
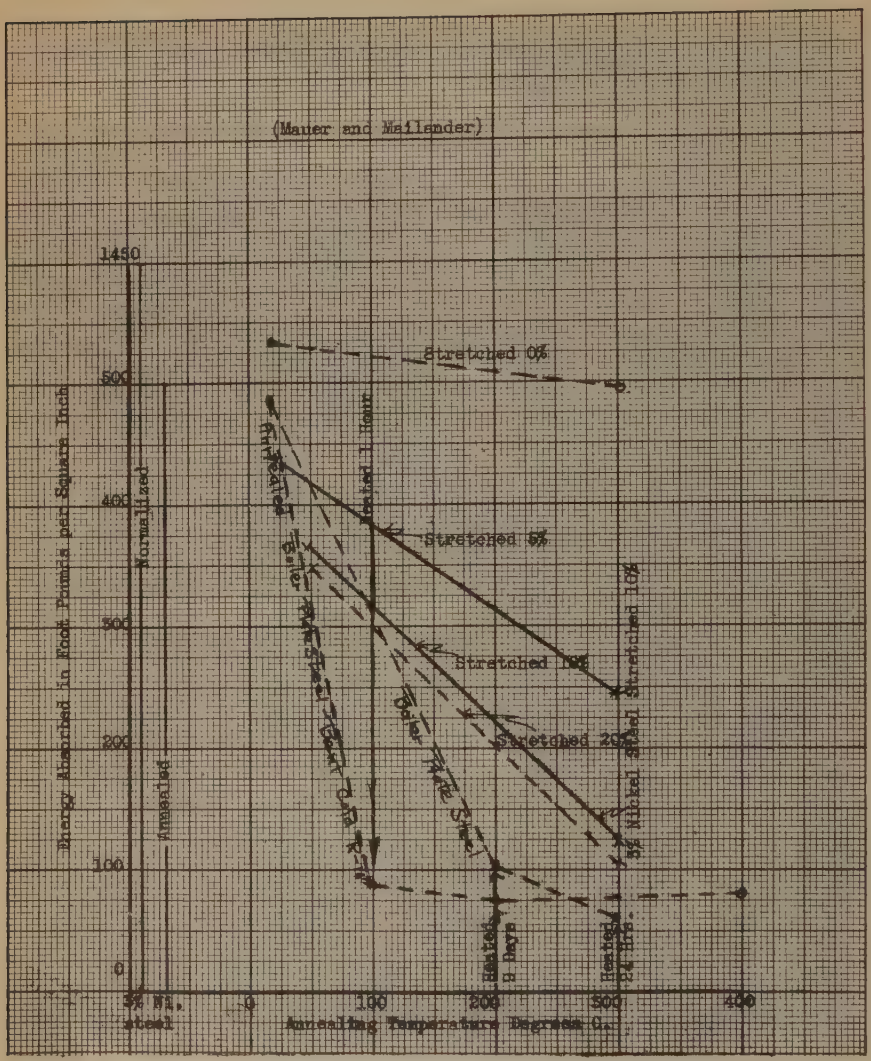


Figure 14 Effect of Annealing Temperature on the Charpy Impact Toughness of Cold Drawn 0.30% Carbon Steel.


(Mauer and Mailander)
1450
500
400
300
200
100
0
Energy Absorbed in Foot Pounds per Square Inch
Stretched 0%
Stretched 5%
Stretched 10%
Stretched 20%
Stretched 50%
Annealed
Normalized
Annealed
Normalized
Annealed
Normalized
Annealed
Annealed
Annealed

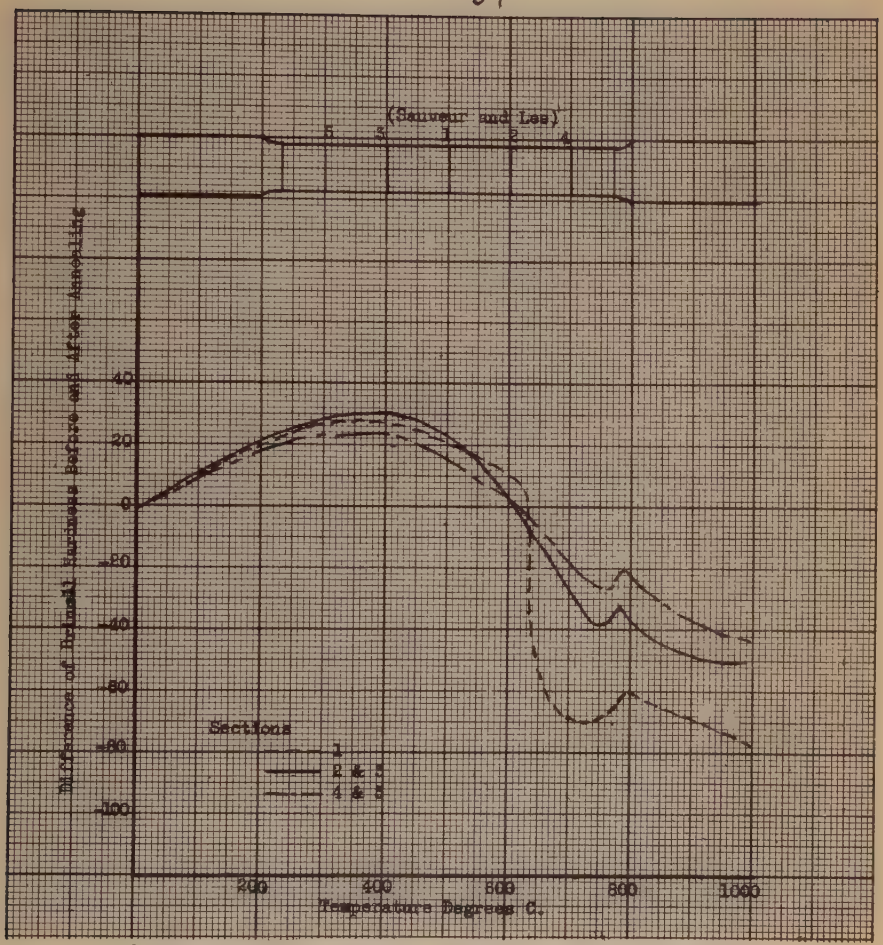


Figure 16 Difference in Hardness at Room Temperature Before and After Annealing 0.50% Carbon Steel.

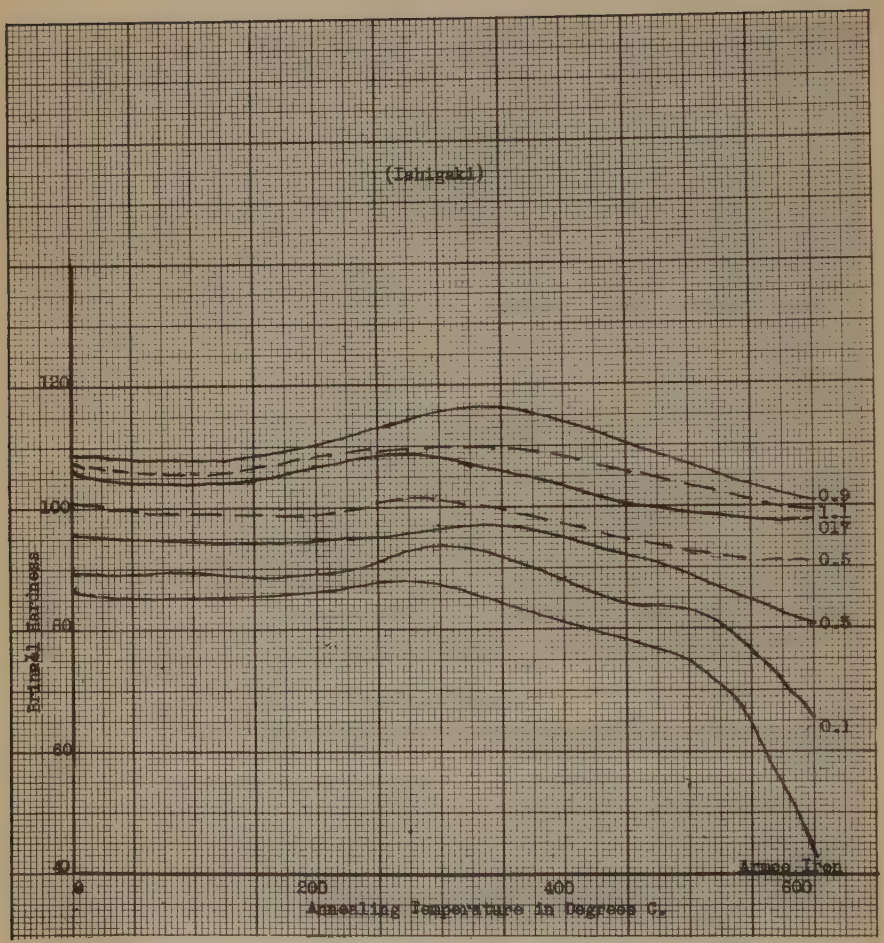


Figure 17 Brinell Harndess of Severely Cold Worked Iron and Steels.

steel have their hardness increased slightly by annealing the specimens from 250° to 350° C., whereas it decreased somewhat rapidly when tempered at a temperature above 470° C.

Spalding[33] in 1926 used the three following types of steel in his investigation.

	Size	C.	Si.	Mn.	P.	S.	Ni.	Cr.	Va.
Mn. Steel	A 19-32 in.	.28	.05	.77	.049	.056			
" "	B 17-32 in.	.32	.19	1.44	.068	.062			
" "	C 1- 2 in.	.27	.08	.96	.070	.054			
Ni Steel	A 19-32 in.	.25	.23	.60	.015	.011	3.37		
" "	B 17-32 in.	.32	.23	.60	.015	.011	3.81		
" "	C 1- 2 in.	.25	.23	.60	.015	.011	3.41		
Cr. Va. Steel	A 19-32 in.	.27	.37	.75	.012	.026	.19	.095	.19
" " "	B 17-32 in.	.27	.37	.75	.012	.026		.098	.16
" " "	C 1- 2 in.	.27	.37	.75	.012	.026		.095	.19

The physical properties of these steels, cold drawn 42.5, 28.1, and 18.9% respectively, followed by annealing at temperatures ranging from 0 to 1400° C. were determined. The curves in Figures 18-21 give the test results. The conclusions reached as stated by Spalding are:

"1. The yield points for Mn. 3.5, Ni., and Cr. Va. steels are considerably increased after cold drawing and reheating to 600° F. (315° C.). The tensile strength is only slightly increased. There is a slight loss in the ductility and notched bar toughness.

2. At 1000 and 1200° F. (540 and 595° C.) the yield point and tensile strength are reduced to their initial figure while the ductility and notched bar figures have made considerable gain over their initial values.

3. The Cr. Va. steels require a higher reheating temperature to restore their normal physical condition (a proper balance between the tensile strength and ductility)."

In determining the influence of cold rolling and subsequent annealing on the hardness of mild steel (C. 0.10% P. .04% Si. Trace, Mn. 0.43%, S. .045%), Edwards and Kuwada[8] in 1927 obtained the curves shown in Figures 22 and 23. These curves show the following features as related by the authors:

"Broadly speaking, the curves can be divided into three distinct ranges, 0 to 500 or 600° C. where there is little or no tendency for the hardness to decrease; in many instances there is an increase. The upper limit of this range varies from 500°

C. with high degree of cold work to 600° C. for low degree of cold work. The second range of temperature is that over which the hardness induced by cold rolling is comparatively removed, namely from 500 to 600° C. for high degree of cold work, and from 600 to 650° C. for low degrees of cold work. The third temperature range is that over which cold work hardening has been removed, and little further change takes place on raising the temperature to 750° C."

From the curves it can be seen that the slope corresponding to the removal of cold work hardening increases and the minima of the curves move to the left with the degree of cold work put on the specimen. The authors, however, failed to make tests on material reheated below 500° C.

In his investigation on the effect of annealing on the properties of cold drawn tubes (0.35, 0.3, 0.5, and 0.19% C.) Lea,[24] in 1927 concluded that:

"Cold drawn tubes, after the final pass, have a low limit of proportionality, but the strength is much higher than that of normalized material. Up to a percentage reduction of from 25 to 30%, the statical properties of the tubes are increased. Annealing the tubes at various temperatures changes the strength in tension and in compression at about 350° C. to 400° C. The limit of proportionality of cold drawn steel tubes in compression may be increased more than 300% and that of tubes in tension 30% by heat treatment at temperatures between 360 and 480° C. After 480° C. the effect of heat treatment is to cause a very rapid lowering of the limit of proportionality, the ultimate strength, and the fatigue range. The limit of proportionality, the ultimate strength, for tensile and compression, the yield point, all pass through a minimum after annealing temperature above the normalizing temperature, all the properties of the tubes increase, this increase being more marked in tubes that were annealed below the normalizing temperature before the last pass than those heat treated above the normalizing temperature before the last pass. The maximum of elasticity of cold drawn steel tubes in compression is raised by heat treatment. The change is not more than from 5 to 10% and the experimental points do not follow closely to the mean curve, but for all sets of tubes there seems no doubt that the maximum of elasticity in the cold state is lower than after

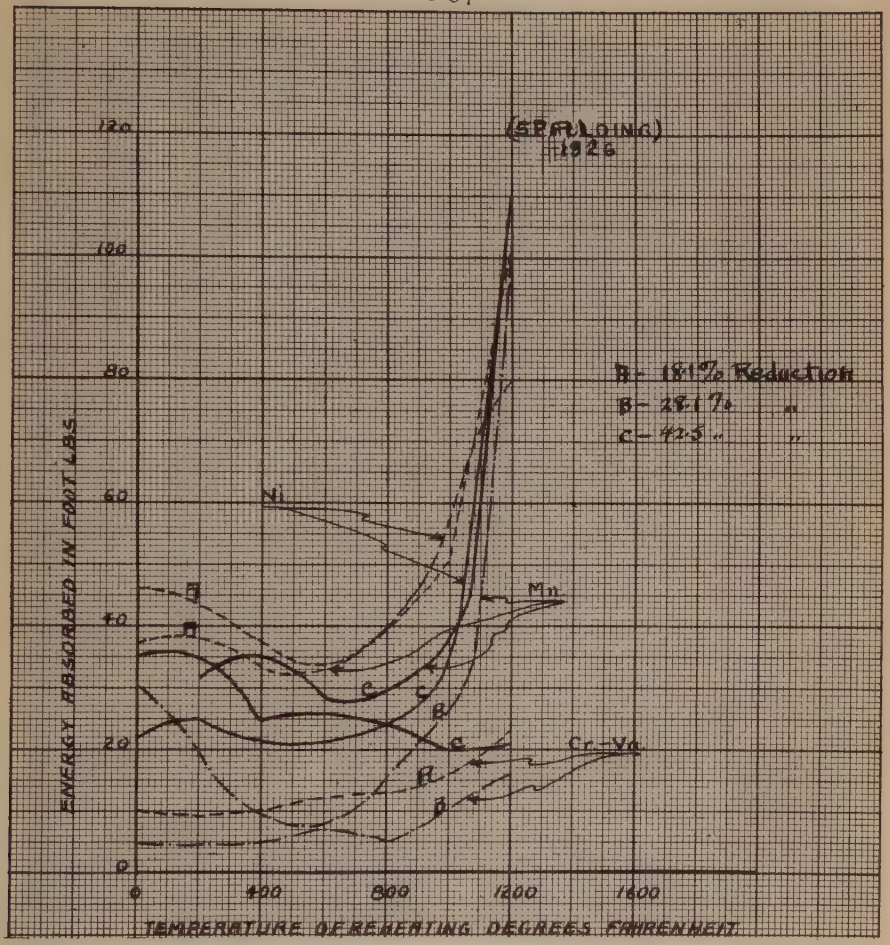


Figure 18 Izod Impact Curves of Ni., Mn., and Cr.-Va. Steels Cold Drawn One Pass, Reheated to Various Temperatures for 30 Minutes and Then Quenched in Water, Determined at Room Temperature.

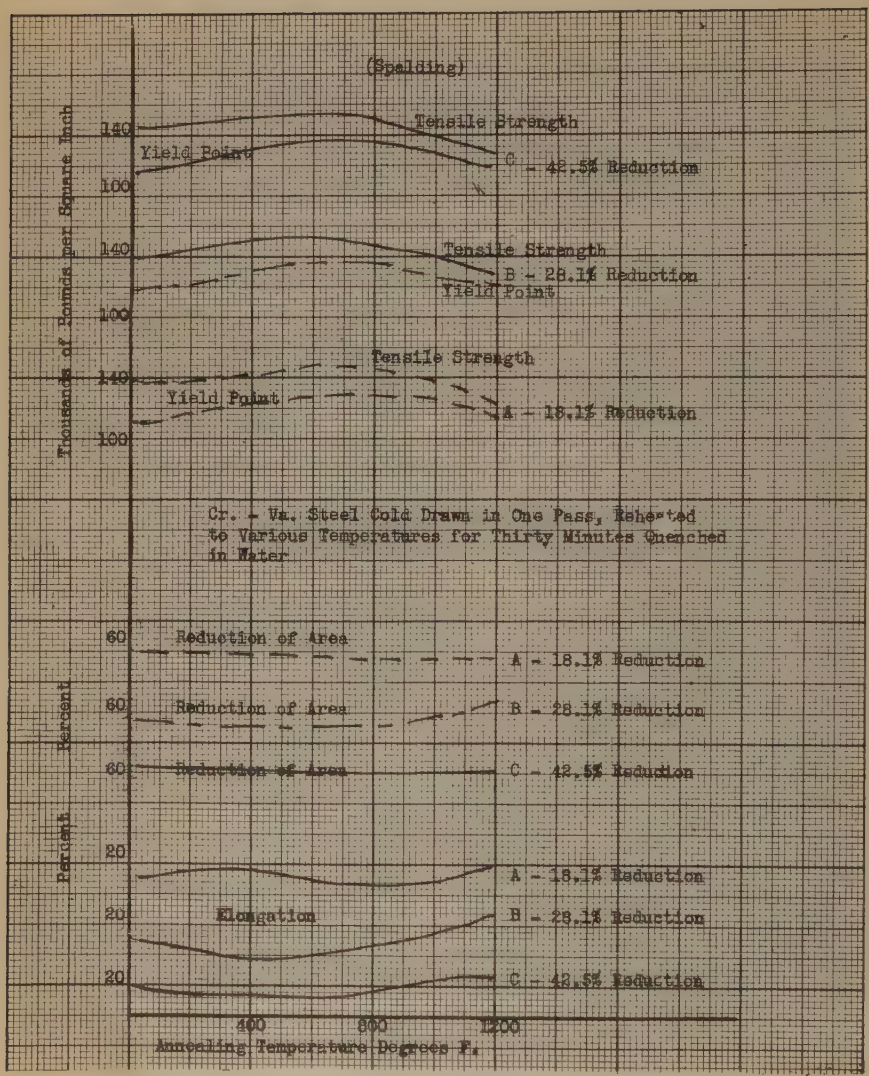


Figure 19 Physical Properties of Cr.-Va. Steel Cold Drawn in One Pass, Reheated to Various Temperatures for 30 Minutes, Quenched in Water.

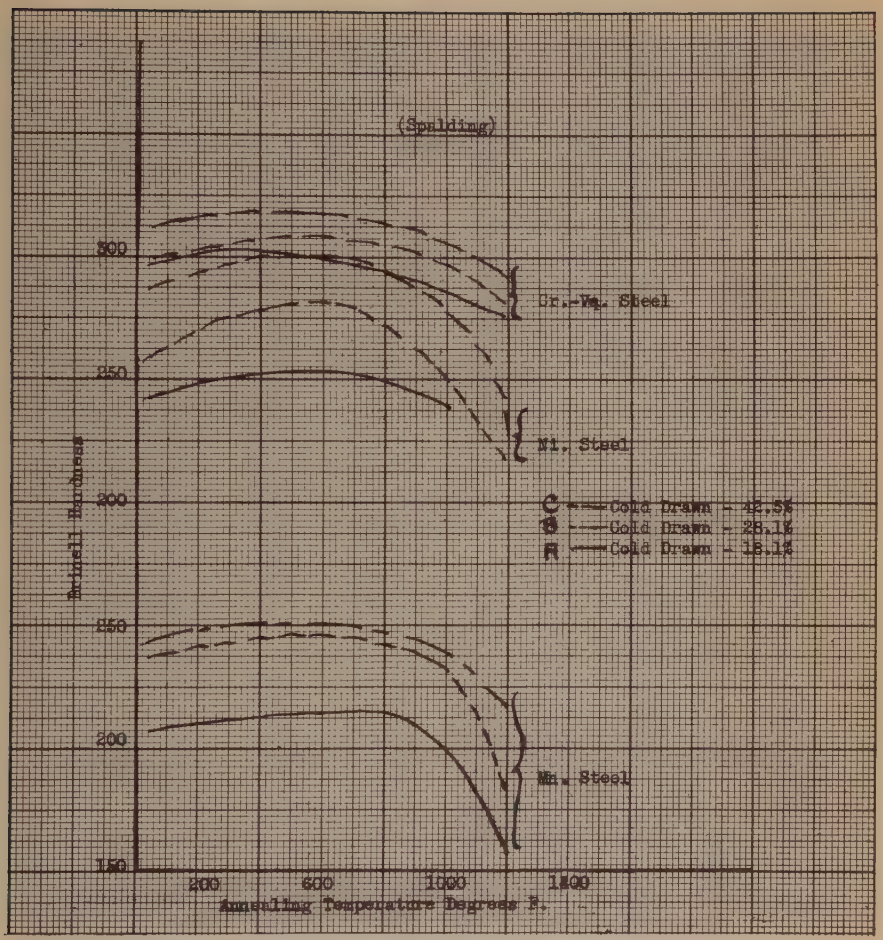


Figure 20 Brinell Hardness of Bars Cold Drawn in One Pass Annealed to Various Temperatures for 30 Minutes and Quenched in Water.

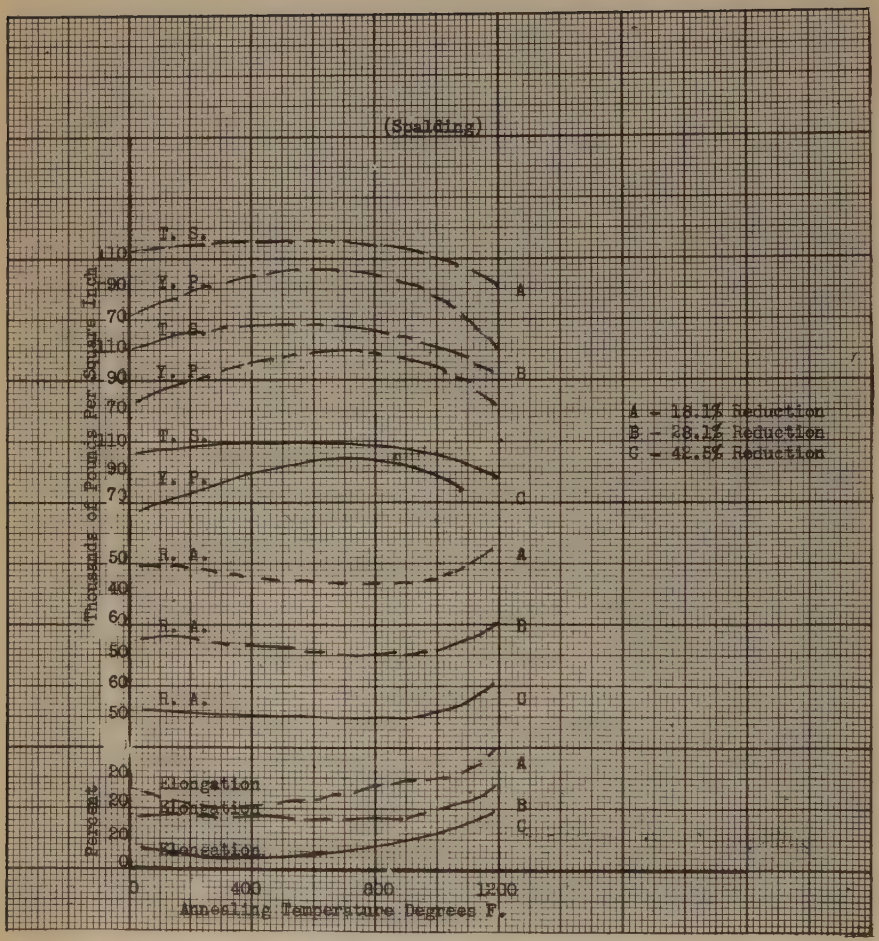


Figure 21 Tensile Tests of Cold Drawn Manganese Steel.

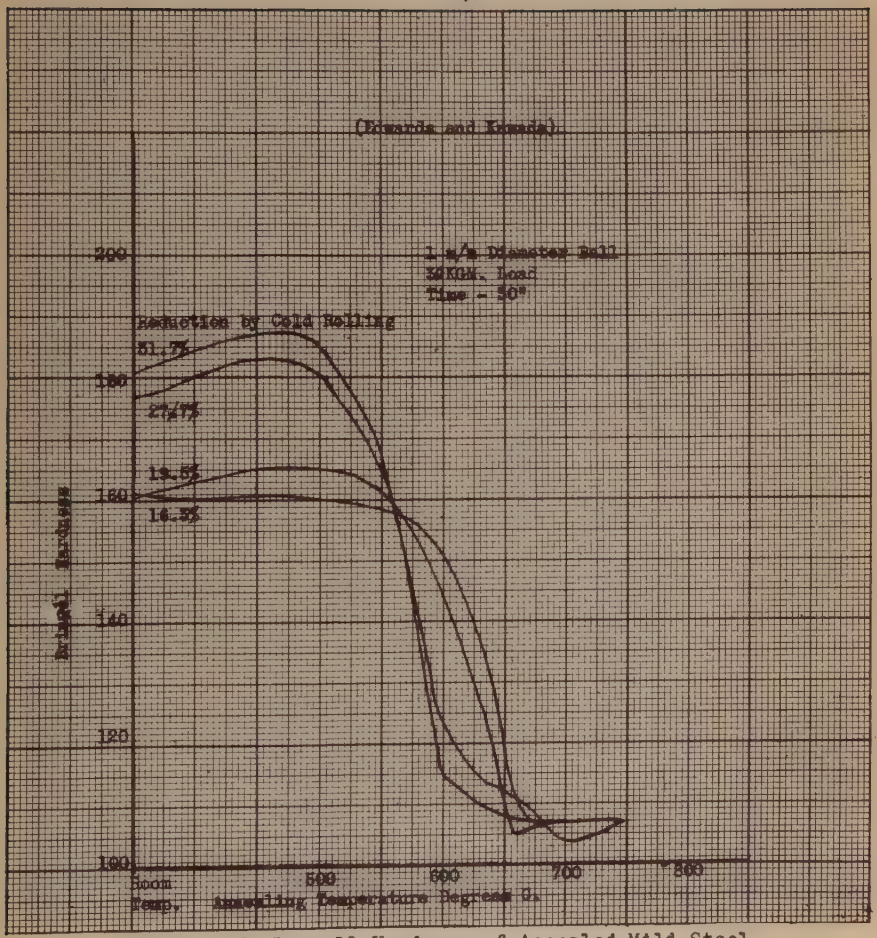


Figure 23 Brinell Hardness of Annealed Mild Steel (0.10%C.) Previously Subjested to Various Degrees of Cold Rolling.

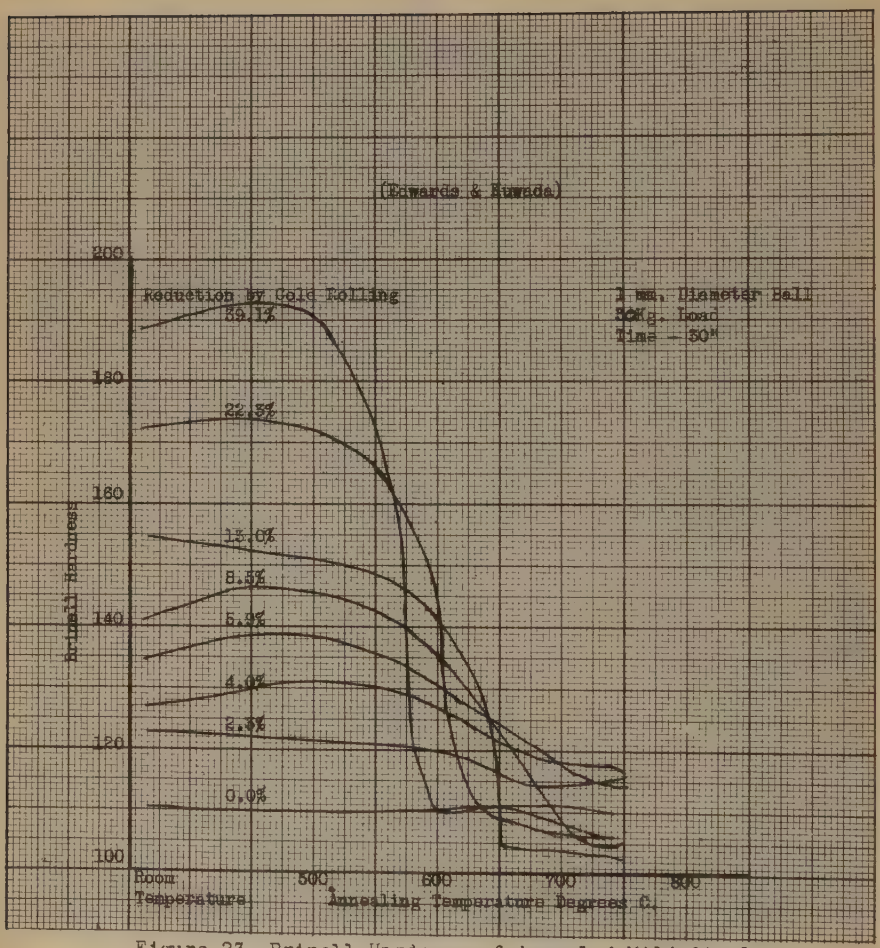


Figure 23 Brinell Hardness of Annealed Mild Steel (0.10% C.) at Various Degrees of Cold Rolling, Tested at Room Temperature.

heat treatment at from 350 to 480° C. and its value passes through a minimum at an annealing temperature of from 650 to 750° C. depending on the carbon content. The maximum of elasticity obtained from bending tests is more uniform. The maximum of rigidity, as obtained from torsion tests, is also affected by heat treatment and approximately reaches its maximum value after annealing at 400° C. The effect of heat treatment on cold worked tubes normalized before the last pass, is to raise nearly all the properties, as compared with cold worked tubes, as the temperature of anneal is raised from 100 to 500° C. The table below summarizes these results:

	Annealing Temperatures Degrees Centigrade at Which Maximum Occurs.
Maximum of Rigidity	200-450
Maximum of Elasticity	250-480
Ultimate Shearing Stress	300-420
Limit of Proportionality	360-480
Crushing Stress	300-360
Hardness	350
Endurance Range	300-420
Density	400-600

Some of the curves from which Lea drew the above conclusions are shown in Figures 24, 25 and 26.

Since the physical properties of reheated cold rolled strip steel are of considerable importance, Swinden and Bolsover[34] in 1927 published a paper entitled "Notes on Cold Rolled Strip Steel." Carbon steels (A-0.10% ; B. C, D.-0.70% ; K-0.34% ; and L and N having 0.54% C.) were used which were reduced in cross section by cold rolling 33% and 66% respectively. As a result of their research, the curves in Figures 27-32 were obtained, and they concluded that:

> "The maximum stress in tension increased with the rise of reheating temperature to approximately 300° C. in all steels, with the exception of dead soft strip, and fell with increasing temperatures above this point. Annealing before cold rolling reduced the rise obtained by reheating after rolling.
>
> The resistance to shear also increased up to approximately 300° C. the dead soft strip being affected in the same manner as, but to a less degree than, the remaining steels, the rise again being proportional to the amount of cold rolling.
>
> Not only did the Brinell hardness rise on reheating but the

ratio to the maximum stress fell, thus giving a higher proportional rise for the Brinell number than for the maximum stress."

A theory which should account for the increase in hardness for steel cold worked subsequent to annealing was advanced by Grossman and Snyder[14] in 1928. In substantiation of this theory they submit the curve in Figure 33 which shows a maximum increase in hardness for cold worked steel by reheating to 600° F. (315° C.). The authors used 3.5% nickel steel, compressed from 1 inch diameter cylinders to one-half their former diameter. (Figure 34.) The theory advanced is essentially as follows: A thin layer of "interblock" material is formed by cold working which upon annealing increases gradually in thickness as the temperature is raised. The maximum effective thickness occurs at approximately 315° C. Dean[14] in his discussion of this paper furnished the curves for iron listed No. 1, 2, and 3, shown in Figure 33.

Rees[32] in 1928 again investigated the physical properties of stream line steel wire (C. 0.42, Si. 0.29, Mn. 0.56, S. 0.041%) which had undergone cold working in six holes from 0.375 in. by 0.217 in. to .025 in. by 0.06 in., followed by annealing. The effect of annealing at low temperature on the proportional limit was relatively the same for both series of wires, the maximum value being reached at 300° C. The ratio of tensile strength to Brinell hardness numbers, which was raised considerably by cold drawing, was reduced progressively by subsequent heat treatment. It fell from 0.25 to 0.20 as the temperature of heat treatment was raised to 600° C.

Recently, Bauer[2] found that the addition of a small amount of Cu. (0.13%) to mild steel which had been cold worked by compression followed by heating had its toughness also reduced but the values obtained were far in excess of those for ordinary mild steel, (Figure 35), at every temperature of reheating from 0 to 600° C.

The steels used in his research had the following chemical composition:

	Izett No. 1	A	B	C
C.	.13	.28	.2	.07
Si.	.02	.—	.—	.—
Mn.	.58	.50	.39	.35
P.	.012	.019	.026	.009
S.	.015	.041	.031	.014
Cu.	.19	.13	.09	.04
As.	.035	.019	.045	.028
Ni.	—	.01	—	—
Cr.	—	.03	—	—

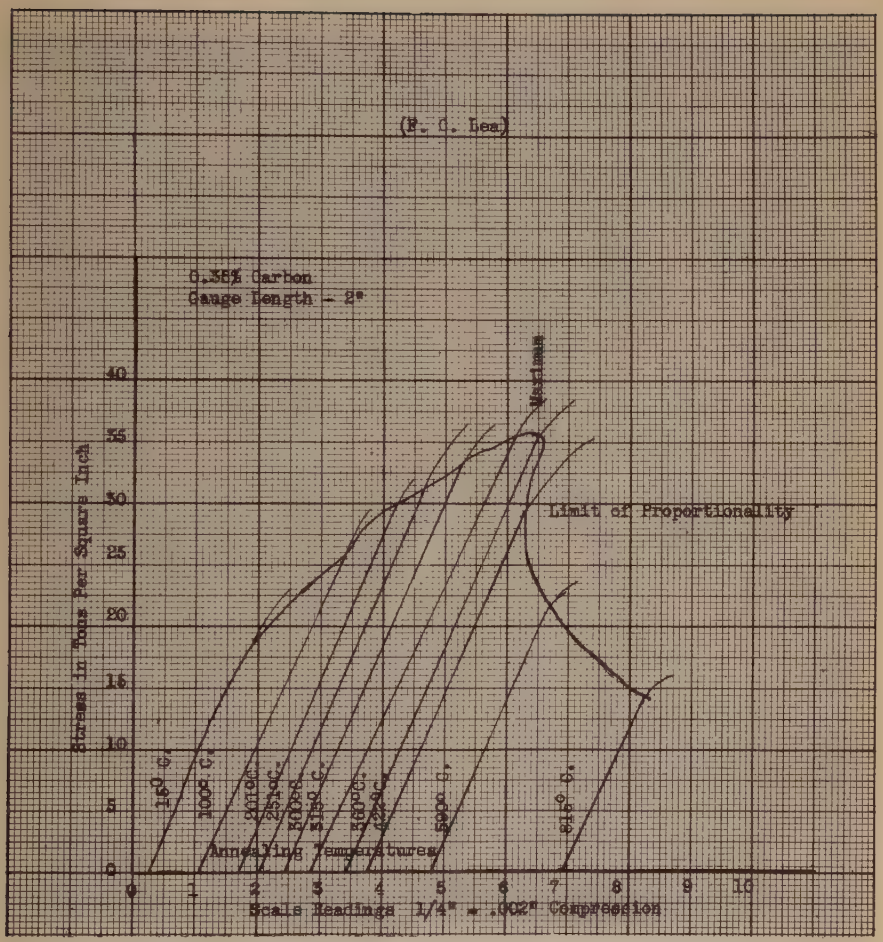


Figure 24 Compression Tests on Cold Drawn Steel Tubes Annealed at Various Temperatures. (Heat Treatment Between Passes Above Normalizing Range.)

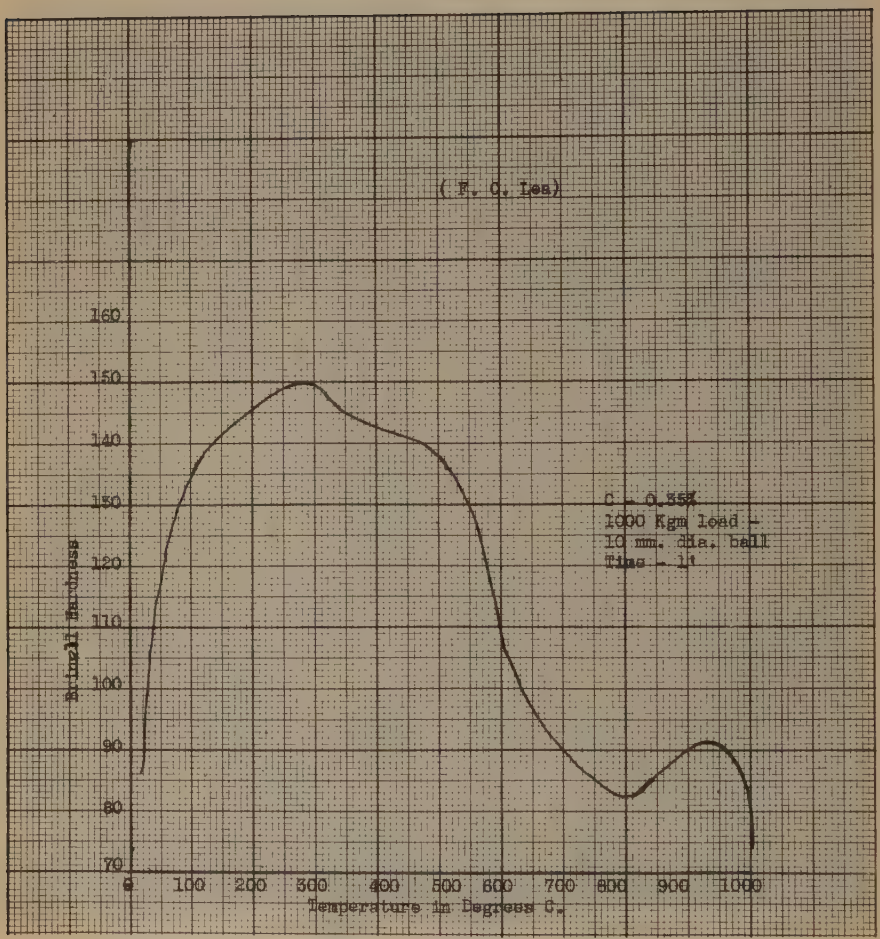


Figure 25 Brinell Harndess Values at Room Temperature

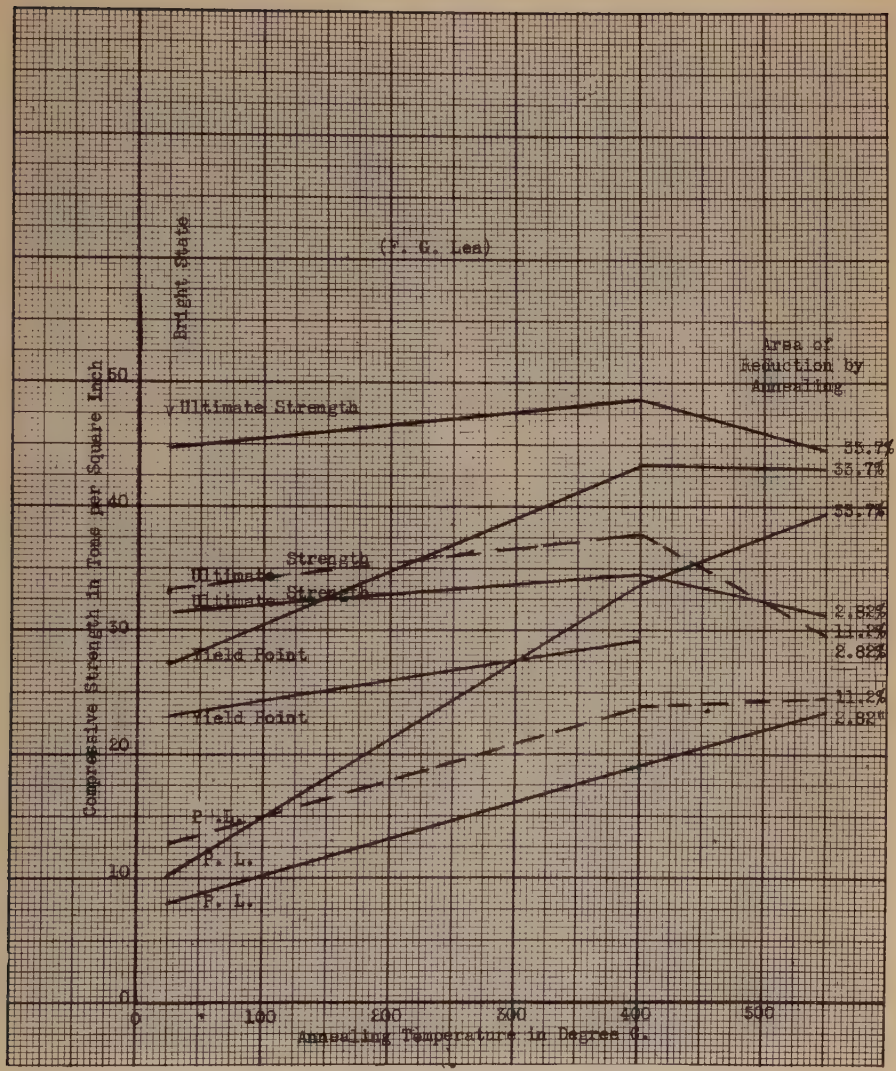


Figure 26 Compression Strength of 0.3% Carbon Steel.

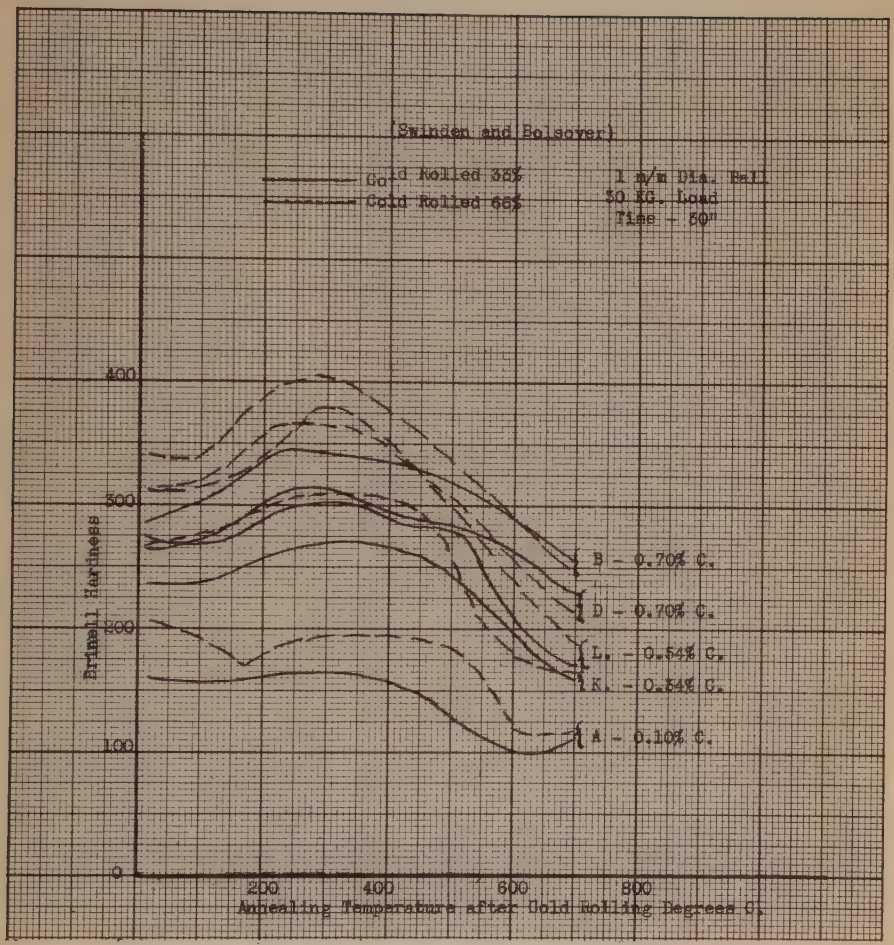


Figure 27 Brinell Hardness at Room Temperature of Steels A, B, D, K, and L, Cold Rolled 33 and 66⅔ Respectively, Followed by Annealing.

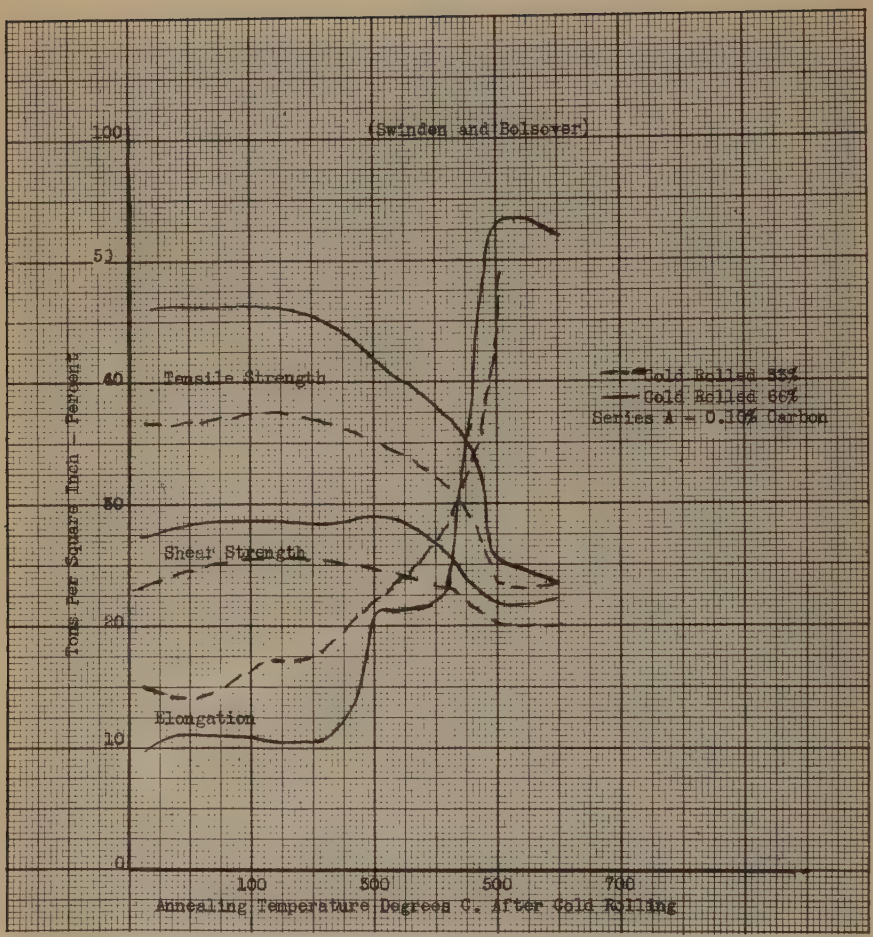


Figure 28 Tensile Properties of 0.10% Carbon Steel Annealed Prior to Cold Rolling 33% and 66% after Heating to Various Temperatures, Tested at Room Temperature.

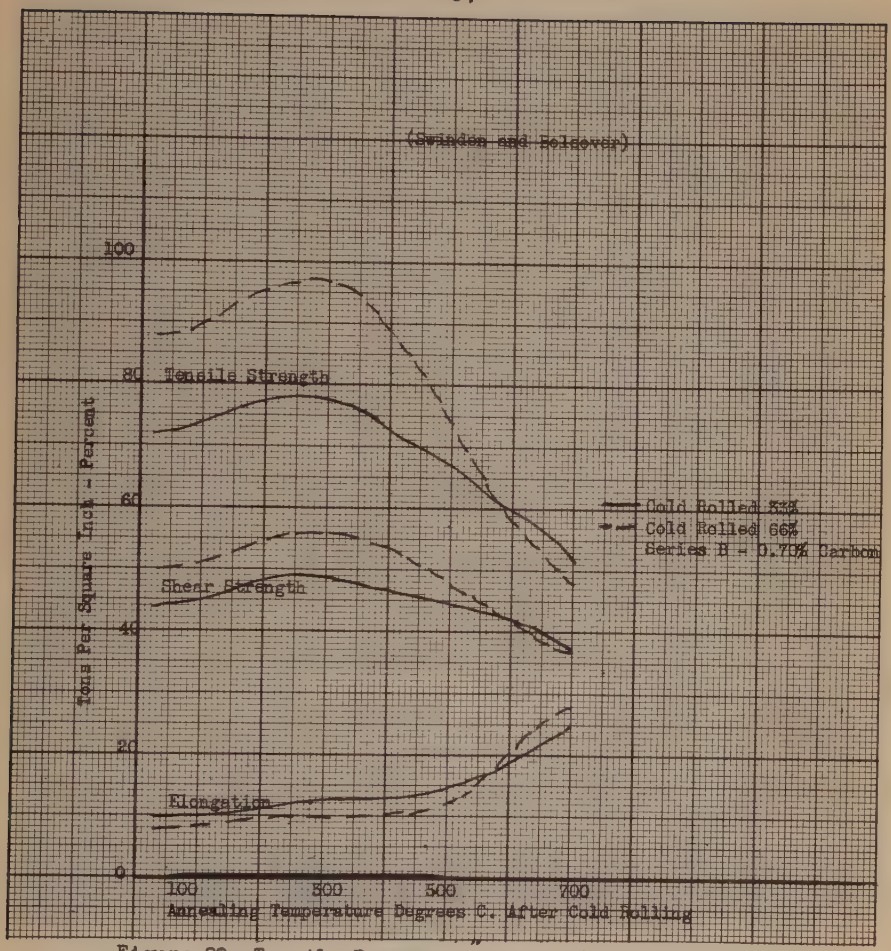


Figure 29 Tensile Properties of 0.70% Carbon Steel Annealed Prior to Cold Rolling 33⅓ and 66% after Heating to Various Temperatures, Tested at Room Temperature.

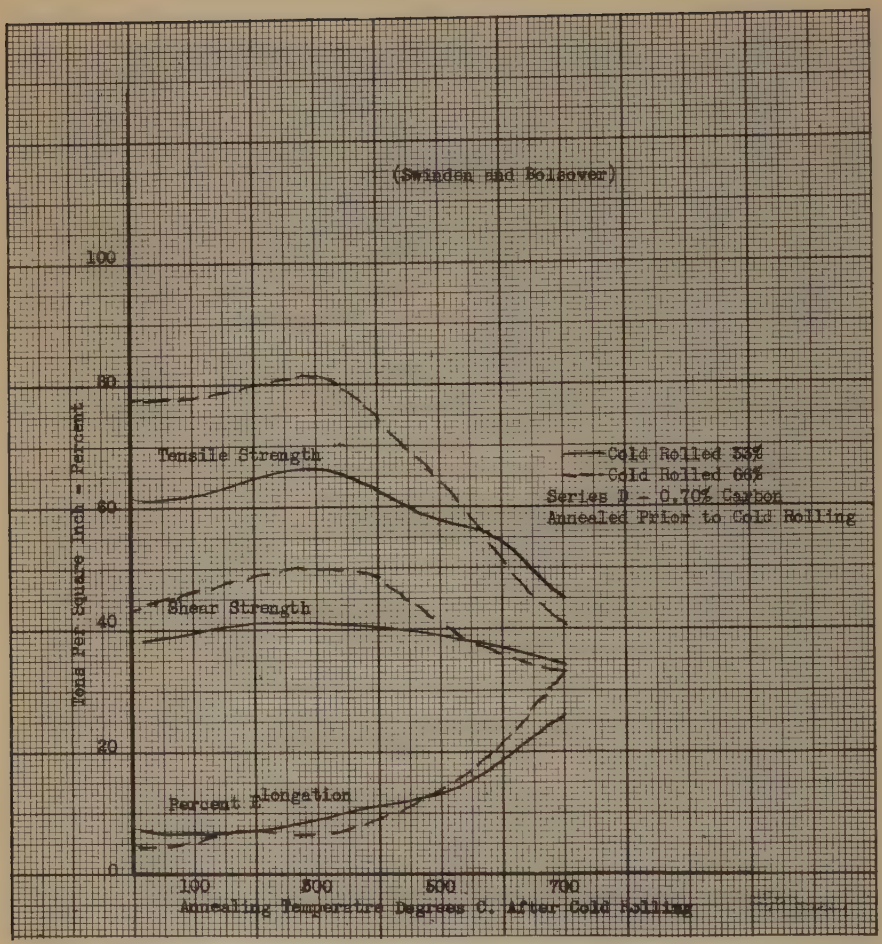


Figure 30 Tensile Properties of 0.70% Carbon Steel Annealed Prior to Cold Rolling 33% and 66% after Heating to Various Temperatures, Tested at Room Temperature

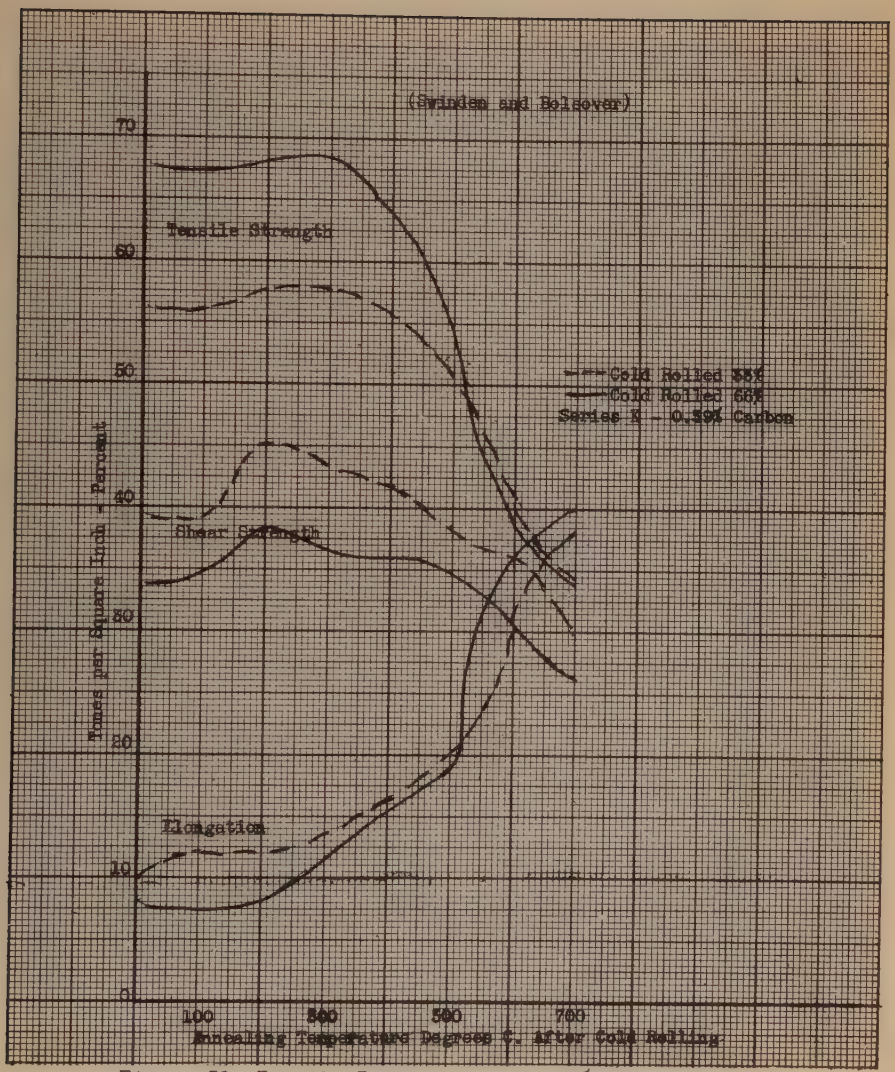


Figure 31 Tensile Properties of 0.39% Carbon Steel Annealed Prior to Cold Rolling 33% and 66⅔ after Heating to Various Temperatures, Tested at Room Temperature.

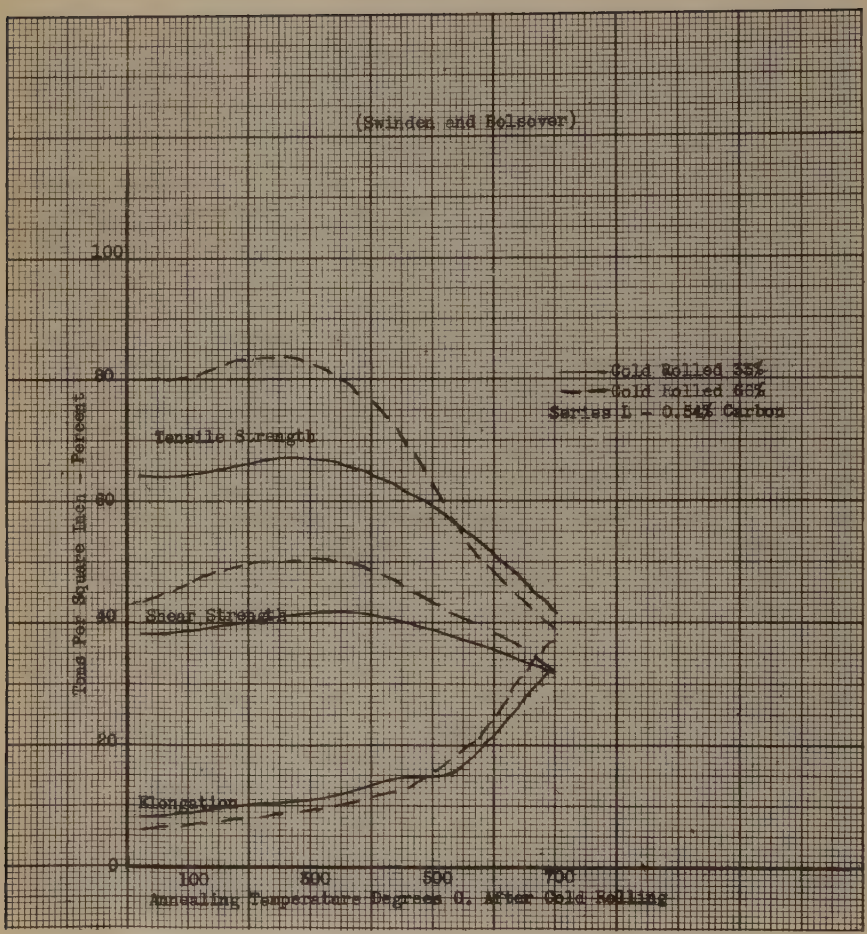


Figure 32 Tensile Properties of 0.54% Carbon Steel Annealed prior to Cold Rolling 33% and 66% after Heating to Various Temperatures, Tested at Room Temperature.

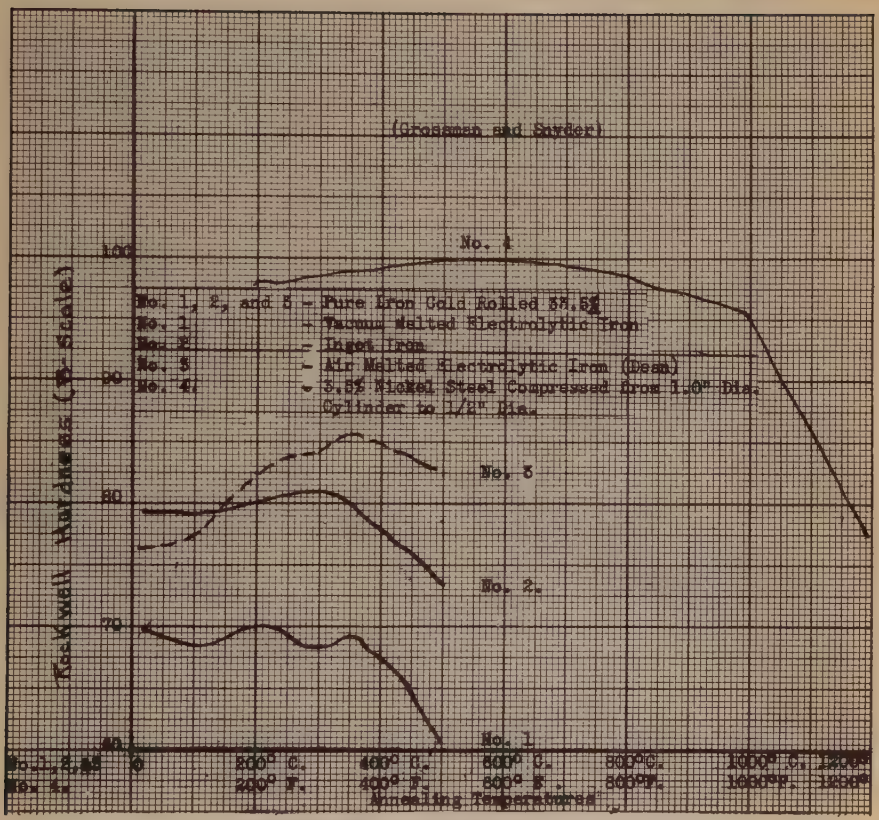


Figure 33 The Rockwell Hardness of Cold Worked 3.5% Nickel Steel and Pure Iron Annealed as Shown.

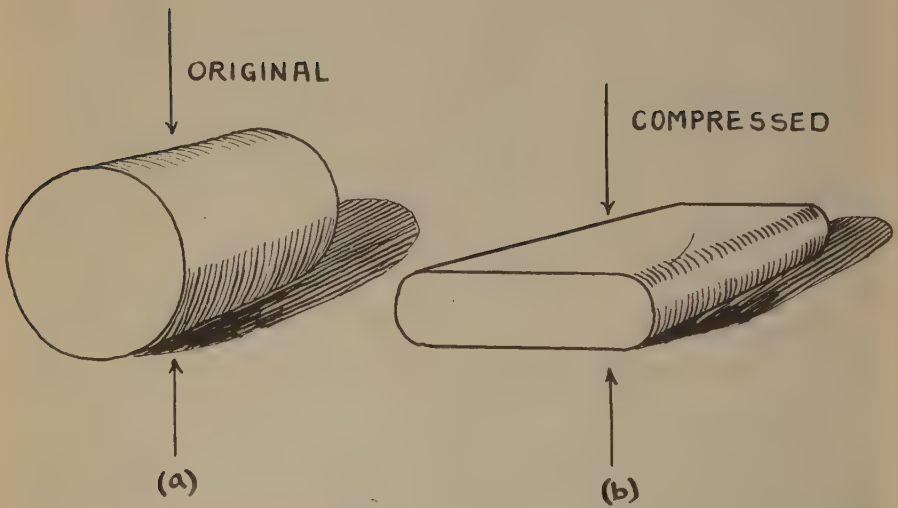


Figure 34 Round Steel Bars as (a) Compressed to (b)

(Grossman and Snyder)

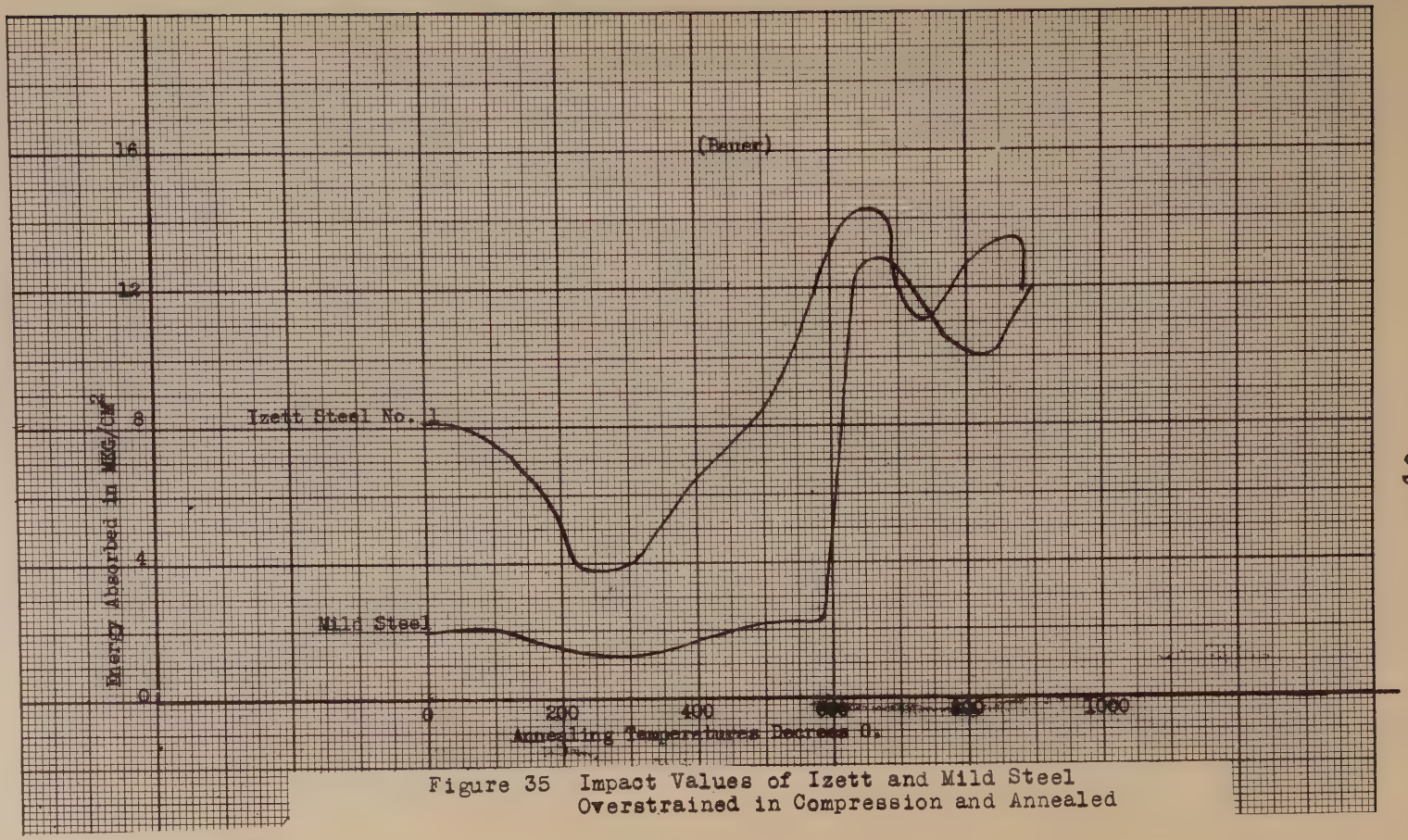


Figure 35 Impact Values of Izett and Mild Steel Overstrained in Compression and Annealed

In May, 1929, Bolsover[39] published a paper entitled "Brittleness in Mild Steel," in which he gives figures and curves showing that this steel had its ductility reduced whenever it was cold worked certain degrees prior to annealing at low temperature for thirty minutes. The lowest impact figures were obtained when this steel was cold worked by extension 15% prior to annealing at 250° C. for thirty minutes. (Figure 36.)

Figure 37 on the other hand reveals that annealing at 250° C. steel which had been elongated 10% also reduced its shock absorbing properties to a minimum. Bolsover, however, failed to make a complete series of static tests (tensile) as well as bend, in conjunction with the dynamic (Izod), from which comparative conclusions could be drawn.

Table I is a tabulated summary of the review of literature which has been discussed in this section.

DISCUSSION OF THE WORK OF PREVIOUS INVESTIGATORS

Tension Tests

In general it may be said that steels which have been deformed prior to heating below the critical range have their physical properties altered. Static testing reveals the following features:

1. The yield point, shear strength, tensile strength and hardness, as a rule, increased, attaining a maximum value at approximately 300° C. In certain cases, however, the maximum occurred within the range of 200-250° C. Heating above 300° C. showed a very rapid decrease in the physical properties mentioned above.
2. There is not sufficient evidence to correlate the percentage of cold working prior to heating with the physical properties of the material. In general, however, the yield point, tensile stress, and elastic limit tend to increase with the percentage of deformation followed by heating.
3. It is not possible, from previous results, to definitely specify an annealing temperature at which a minimum value in toughness can be obtained. Toughness tends to decrease when the material is annealed within the temperature range of 150-350° C. In some instances, there is a slight increase at 300° C., but usually heating beyond this temperature is necessary before a decided rise in toughness becomes apparent.

4. The investigation of Van den Broek shows this important feature:

   "The same heat treatment applied to a steel, deformed in different manners (compression, tension, cold-drawing, cold-rolling) will not produce the same changes in the physical properties. Comparative results can be drawn only from steels affected similarly."

5. In most of the previous researches, little or no attention was given to the treatment of the materials prior to the investigation. The percentage cold work by compression, tension, bending, etc., as well as the original condition of the material, was not sufficiently emphasized.

6. In most cases where the materials were deformel by compression, the amount in per cent was not given. In those instances where the degree of cold work (cold drawing, elongation, etc.) was given in per cent, we find that the deformation was in the following amounts. 0-16, 0-20, 0-39, 8.1, 12, 14.8, 18.4, 25-30, 28.1, 33, 35, 42.5, 48, 66, 85%.

7. Most investigators on this subject were interested in some particular phase of the change in physical properties; thus we find an inadequacy of results for the correlation of mild steel under static and dynamic stresses.

Notched-Bar Impact and Bend Tests

The chief advantage of notched impact testing over static testing is its ability to reveal the brittleness of material. This is usually determined by subjecting test pieces to sudden loads (shock). The bend test, however, is also another method whereby the brittleness of materials can be detected. Although its fullest importance is still undecided, it is, as a whole, accepted as a qualitative measure of brittleness.

1. Generally speaking, most cold worked steels show a pronounced brittleness when heated to about 300° C. In some researches, minimum values were found after heating at 200° C., as well as 250°C. This minimum value is also dependent on the chemical composition and the condition of the original material, as well as the degree of plastic deformation imparted to the material before testing. It appears, however, that by heating to 550° C., this pronounced brittle-

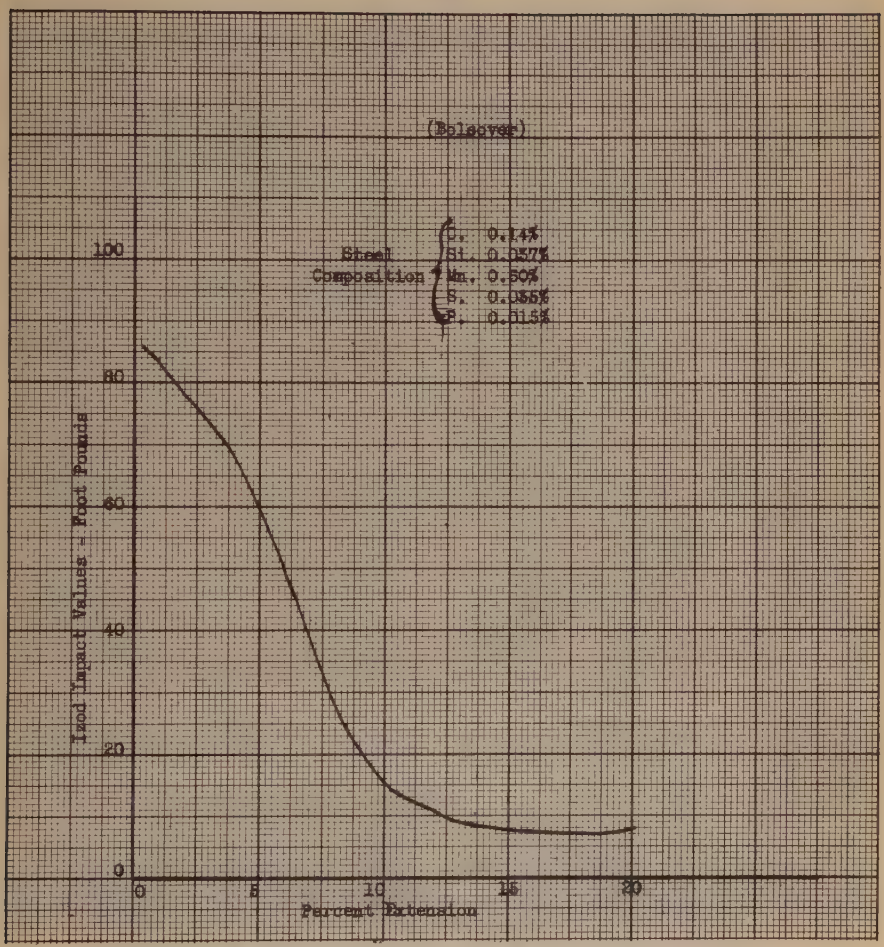


Figure 38 Izod Impact Values of 0.14 Carbon Steel Cold Worked by Extension Various Amounts Followed by a 30 Minute Anneal at 250° C.

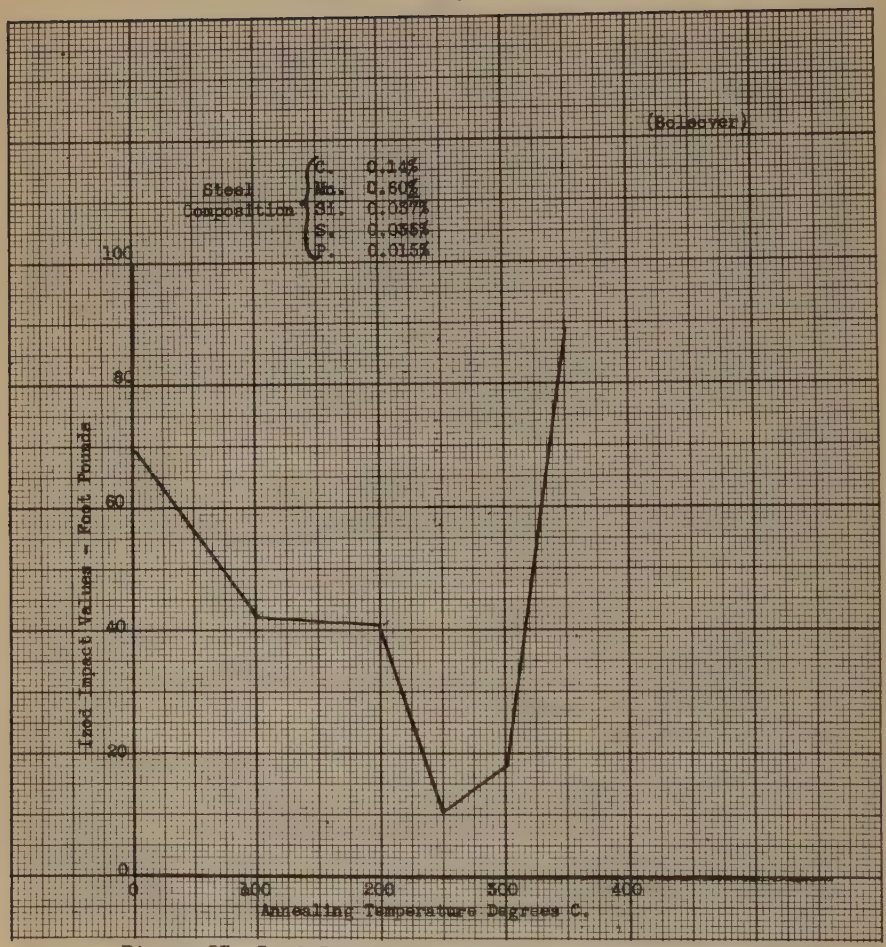


Figure 37 Izod Impact Values of Dead Soft Steel Cold Worked 10% by Elongation Followed by Annealing for Periods of 30 Minutes.

TABLE I

Author	Material Investigated	Annealing Temperature	Treatment of Specimens	Tests Performed	Conclusion of Authors	References
Bauschinger, J.	Mild Steel	100-200° C.	Cold worked prior to annealing	Tensile Tests	Elastic properties improved by ageing and tempering	Effect of cold working on the physical properties of steel. Mitteilungen a.d.Mechanisch-Technischen Labor. der K. Tech Hochschule in Munchen,1886. Vol. 13.
Muir, J.	Iron	100° C.	Cold stretched prior to immersing in Water	Hysteresis Tests		On the Recovery of Iron from Overstrain. Phil. Trans. of Royal Society of London, 1900. Vol. 193
Van den Broek,J.	Steels (0.16, 0.21 0.26, 0.95)	0-300° C.	Cold stretched and compressed to heat treating	Tensile Tests	Elastic properties bettered, the proportional limit of mild steel in tension doubled while still retaining approximate original proportional limit in compression	The Effect of Cold Working on the Elastic Properties of Steel. Comm. Sch. Mem. Iron and Steel Institute, Vol. 9, also engineering July, 1918.
Stromeyer, C.E.	Mild Steel	0-300° C.	Compressed and bending prior to ageing and heat treating	Blows with a hammer	Both ageing at room temperature and tempering at 250-300° C. made mild steel brittle.	Ageing of Mild Steel, Journal of Iron and Steel Institute, No. 1, 1907, p. 200-221.
Goerens, P.	0.08% C.steel wires	0-1200° C.	Cold drawn 85% prior to heat treating	Tensile & Bend tests	Critical temperature range from 520-580° C. is where a sudden revision in the physical properties occur	The Influence of Cold Working and Annealing on the Properties of Iron and Steel. Carn. Sch. Mem. Journal of Iron and Steel Institute, 1911.
Bauman, R.	Mild Steels	0-approx. 350° C.	Compressed prior to heat treating	Tensile, bend, and impact tests	Mild steel compressed will become brittle only after reheating around 100-350° C. Should amplify tests now in use to warrant good steel.	Testing Iron Plates for Brittleness, Zeit. d. Vereines Deutscher Ingenieure. Vol. IX, 1915, pp. 57-60.
Houghton Wolff Milton	Boiler Plate Material low temps. " " " 0.14%C " " " " " " "		Compressed by riveting prior to heating.	Blow from impact hammer	Brittleness of material observed " " " " " " " "	The Failure of Boiler Plate in Service and Investigation of the Stresses that Occur in Riveted Joints. Journal of Iron and Steel Institute, 1917, No. 11, pp. 137-179.
Bauer, O.	Mild Steel 0.29% C.	0-600° C.	Cold drawn approx. 12% prior to low temperature heating	Tensile & Impact tests	Static tensile strength increases between temperatures of 300-400° C. whereas the impact resistance decreases in the same range of temperatures.	Mechanical Tests of Mild Steel, Stahl und Eisen, 1916, Vol. 36. pp. 484-489.
Heyn, E.	Steels			----------	Discussion - Elastic limit and yield point entirely altered by low temperature annealing subsequent to cold working.	Internal Stresses in Cold Worked Materials. Stahl und Eisen, 1917, Vol. 37, pp. 442-448, 474-479, 497-500.
Bauer, O.	0.12% C. steel	0-800° C.	Cold Worked by compression subsequent to heating	Impact test	A minimum value in impact toughness found between 250-300° C.	Boiler Plate Failures, Stahl und Eisen, May 23, 1918, Vol. 38, pp. 456-468.
Fettweis,	Mild Steel	0-500° C.	Cold worked subsequent to heating	Tensile tests, Bend and impact	Cold worked material subsequent to reheating becomes brittle. Ageing increases the effect as well as deforming the steel at a blue heat.	Tensile Strength of Steel at High Temperatures, Blue Brittleness and Ageing of Steel. Stahl und Eisen, Jan. 2 and 9, 1919. Vol. 39, p. 1-7, 34-41.
Adams, H.T.	Steels 0.42-0.46% C.	0-800° C.	Cold rolled 35 and 48% subsequent to heating	Tensile & Bend tests	Any form of heat treatment as a whole has a deleterious effect on the toughness of steel.	Relation of Heat Treatment to Cold Work in Hypo-Eutectoid and Eutectoid Steel Carn. Sch. Mem. 1920, Vol. 10, pp. 65-128.
Jones, R.M. & Greaves, R.H.	A. 0.32 C. B. 0.26 C. 3.53 Ni. 0.84 Cr. C. 0.32, 2.12.Ni. 1.45Cr.	0-200° C.	Cold worked by tension 0-1; 0-16% C.D. compress. 0-16% aged at room temp. & at 100 and 200° C. resp.	Tensile & Impact (Izod)	The impact values decrease to a greater extent after elastic recovery than immediately after straining. (All steels were originally oil hardened and tempered).	Effect of Overstrain on the Impact Figures of Steel. Proceedings of the Institute of Civil Engineers, Nov. 30, 1920, p. 120.
ditto	Statement in reviewing literature of effect of deformation followed by heating on the impact figure curve.					Effect of Temperature on the Behavior of Iron and Steel in the Notched Bar Impact Test. Journal of Iron and Steel Institute, No. D, Vol. cxii, p. 132.

TABLE I (CONTINUED)

Author	Material Investigated	Range of Temperature Reheat	Treatment of Specimens	Tests Performed	Conclusions of authors	References
Greaves, R.H.	Six steels -0.34% C. 0.50% C. normalized 0.77% C. Ni. 3.55, .34% C. Ni. 2.12, .32% C. Cr. 1.45 cast. Ni. 1.98, .30%,C. Cr. 5.23	0-350° C.	Overstrained in compression and tension prior to heating at 100, 200 and 300° C. Heat treated steels	Tensile Tests	Elastic recovery after overstraining is dependent upon chemical composition, previous heat treatment, direction, amount and time of overstraining, as well as temperature and time of recovery periods.	Effect of Overstrain on the Elastic Properties of Steel, Iron & Coal Trade Review, July 18, 1921, Vol. 103, p. 73.
Pomp, A.	0.6% C. .024 Cu.	0-900° C.	Cold rolled 8-16% prior to heating	Tensile, Impact	Annealing between 650-850° C. produces coarsest grain. Physical properties affected. Surface hardness lowered 9-14%; yield point lowered 35 to 47%; notched toughness 9 to 25%.	Critical Heat Treatment after Cold-Working of Low Carbon Steels, Stahl und Eisen, Sept. 23, Oct. 14, 1920. Vol. 40, pp. 1261-1269; 1366-1378; 1403-1415.
Korber, F. Dreyer, A.	Steels: C. Cu. .21 .02 .20 .01 .08 .04	0-400° C.	Pulled approximately 10% prior to heating	Tensile and Impact	Maximum annealing effect attained at 100° C. Notched toughness a minimum when annealed between 200-300° C.	Blue Brittleness and Ageing of Iron. Mitterlungen a.d. Kaiser Wilhelm Inst. fur Eisenforschung. 1921, Vol. 2., pp. 59-89.
Korber, F.	Steel .08 .04	550° C. Ac3 point	Pulled approximately 10% before heating	Tensile and Impact	Static tests failed to show up brittleness whereas impact test brought out this feature well. Coarsely grained material had its elastic limit and yield point lowered one half and one quarter from their original values.	The Mechanical Properties and Structure of Critically Cold Worked and Annealed Mild Steel. Mitterlungen a.d. Kaiser Wilhelm Inst. fur Eisenforschung. 1922, Vol. 4, pp. 31-48. Abstract Jl. I.S.I. 1923, No. 1. pp. 703-704.
Fischer, P.	Mild Steel	Recrystallization Temp. 650 up. Also 200° C.	Pulled	Bend and Tensile	Toughness diminished by heating for long time at 200°C.	Effects on Recrystallization generally and Determination of the Tensile Properties of Recrystallized Mild Steel. Kruppsche Monatshafte, May - June, 1923. Vol. 4, pp. 77-114.
Hillman, E.V. Coonan, F.L.	Low Carbon Steel	650° C. up	Cold worked 8-16%.	Grain Growth	Abnormal grain growth obtained by cold rolling from 8 to 16% prior to reheating above 650° C.	Abnormal Grain Growth in Cold Rolled Low Carbon Steel. Trans. A. S. S. T. August 1923, Vol. 4, pp. 162-170.
Delbart, H.	0.127, 0.4, 0.6,0.3% C. steels	0-900° C.	Cold rolled	Tensile and Charpy Impact tests	Tensile properties are at minimum at 650-700° C. Impact toughness of 0.3% C. steel has a minimum value at 300° C.	The Effect of Reheating Cold Rolled Steels, Comptes Rendus, 1925, Vol. 180, pp. 934-937.
Mauer, E. & Maitlander, R.	Boiler Plate Material and 3.5% Nickel Steel	0-300° C.	Pulled 0-20% prior to ageing and heat treatment	Bend and Impact Tests	Toughness greatly reduced by low temperature anneals. Minimum occurs at 300° C.	Zur Frage der Blausprodigkeit, Stahl und Eisen, 1925, Vol. XIV. p. 409.
Sauveur, A. & Lee, D. C.	0-5% C. steel	0-1200° C.	Pulled till broken prior to heating and testing at fracture.	Brinell Hardness	Maximum increase in hardness occurs at 350° C.	The Influence of Strain and of Heat on the Hardness of Iron and Steel. Journal Iron and Steel Institute, 1925, No. II, pp. 323-329.
Ishigaki, T.	0.1, 0.3, 0.5, 0.7, 0.9, 1.1% C. steels	0-600° C.	Pulled till broken prior to heating and testing at fracture.	Brinell Hardness	An increase in hardness was obtained by heating in range of 250-350° C.; decrease then follows rapidly to a temperature of 479° C.	On the Change in Hardness and the Density in Iron and Steel Caused by Cold Working. Sci. Rep. Tohohu Imp. University, 1926, Vol. 15, pp. 777-794.
Spalding, S.C.	1.44% Mn. 0.32% C. 3.81%, Ni. 0.32% C. Cr. .098, Va. 16%, C. 0.27%.	0-1200° C.	Cold drawn 42.5, 28.1, 18.4% prior to heating	Tensile, Izod, Brinell Hardness	Tensile strength only slightly increased by heating to 315C. There is slight loss in ductility & notched bar toughness at 315°C. Between 540-600°C. the Y.P. and tensile strength are reduced to their initial figures while the ductility and notched bar toughness have made a considerable gain over their initial values.	The Effect of Reheating on Cold Drawn Bars, Trans. A. S. S. T. May, 1926, Vol. 9, pp. 685-716, 780.
Edwards, C.A. Kawada, K.	0.10% C. steel	0-750° C.	0-39% Reduction of area by cold rolling	Brinell Hardness	The slope corresponding to the removal of w-hardening increases; the minimum of the curves move to the left with the degree of cold work.	The Influence of Cold Rolling and Subsequent Annealing on the Hardness of Mild Steel. Journal Iron and Steel Institute. October 1927, p. 245.

Table I (Continued)

Author	Material Investigated	Range of Temperature Reheat	Treatment of Specimens	Tests Performed	Conclusions of authors	References
Lea, F. C.	0.35, 0.3, 0.5, 0.19% C. steels	0-750° C.	Tubes reduced from 25 to 30%	Compression, tensile bend and torsion	Mod. of rigidity - 200-450 (Annealing temperature Mod. of elasticity 250-480 (at which maximum occurs Ult. Shear. Stress 300-420 " " " Limit of Prop. 360-420 " " " Crushing Stress 300-360 " " " Rockwell Hardness 350 " " " Endurance Range 300-420 " " " Density 400-600 " " "	The Effect of Heat Treatment on Cold-Drawn Steel Tubes. Engineering, 1927, Vol. 124, Dec. 23, pp. 797-800; Dec. 30, pp. 831-834.
Grossman, M.A. Snyder, C. C.	3.5% Ni. Steel	0-1200° C.	Compressed to half original size	Rockwell Hardness	A maximum hardness obtained at 515°C. Advanced theory: Added hardness caused by a critical layer of inter block material.	The Influence of Cold Drawing on Mild Steel. Trans. A.S.S.T. 1928, Vol. 13, February. Pp. 201-220, 281.
Swinden, T. Bolsover, G.R.	0.10, 0.34, 0.54 0.70% C. steels	0-700° C.	Cold rolled 33 and 66%.	Tensile, Hardness	Tensile strength, shear strength and Brinell hardness increase up to 300° C.	Some Notes on Cold Rolled Strip Steel, Journal Iron and Steel Institute No. 1, 1927, pp. 569-597.
Rees, S.H.	C. .42%	0-800° C.	Cold drawn	Tensile and Hardness	P.L., Tensile strength and hardness increased by heating up to 300° C.	The Heat Treatment of Steel Wire. Journal of Iron and Steel Institute 1928. Abstract Fuel and Furnaces, 1928. (December).
Bauer, O.	Copper bearing mild steels average about 0.13%	0-800° C.	Cold compressed prior to heating	Bend and Impact	Toughness of these steels much superior to ordinary mild steel, also reduced by reheating; a minimum occured at 300° C.	Flusstahl mit gerninger Atterungseigenschaft. Zeit. d. Bauyrischen Revisions - Vereins (Munich) Vol. 32, No's. 3, 4, February 15 and 19, 1928, pp. 23-31, and 41-44.
Rees, S.H.	0.04 and 0.85% C. steel	0-700° C.	14.8 and 8.1 % cold drawn	Tensile	Annealing at 300° C. raises the elastic limit, tensile strength and yield point.	The Effect of Low Temperature Annealing on Some Mechanical Properties of Cold Drawn Steel. Journal of Iron and Steel Institute, 1923. Vol. II. p. 273.
Bolsover, G.R.	0.14% C. (mild steel)	0-300° C.	cold worked by extension	Impact atvarious temperatures; impact at room temperature after annealing; a few tensile	Ductility as measured by impact test, greatly reduced when cold worked 15% prior to annealing both in temperature range, 200-300° C. for a period of 30 minutes.	Brittleness in Mild Steel. Iron and Coal Trades Review, May, 1929.

ness is, if not wholly, at least partially destroyed. Heat treatment beyond 600° C. restores the material to its original ductile condition.

2. As related in a former passage, the previous treatment of the material has a decided effect on its resistance to shocks.

Failures of steel in service caused by dynamic forces rather than by static occur frequently in industry. An explanation of this cause can be found in a review of the former methods of tests. Since the results of static tests were formerly the chief factor which determined the quality of materials, it became apparent that their abilities to withstand shock were not fully considered. Moreover, there is a lack of knowledge of the different shock-absorbing properties of materials which have been subjected to different treatments. Because of its importance, methods by which the shock-absorbing properties of steels may be determined accurately are becoming an absolute necessity.

Among the French, Fremont[66] and Charpy[65, 53] stand foremost in their work on this subject. In England, Sir Robert Hadfield[67], Hatfield[68] and various members of the British National Physical Laboratory have also dealt at length with this matter. Among the Germans, we can name Mauer, Maitlander[71], Korber, Dreyer, and Pomp[70]. Here in America, the American Society for Testing Materials is at present working on this subject.

The most important conclusion of these investigators is that the result of tension testing is not sufficient to determine the ability of the material to withstand both static and dynamic loads, but that shock tests should always be included to determine both qualities. These shock tests, moreover, should be standardized.

Baumann gives a good illustration of the change in the ability of steel to absorb shocks.

> "The extent to which toughness of a plate is impaired by improper treatment during riveting is clearly brought out in some recent notched impact tests of boiler plate. The average energy absorbed at failure amounted to:
>
> For specimens from the solid plate 11.2 mkg-cm^2.
>
> For specimens from the edge of rivet holes 1.3 mkg-cm^2."

A simple calculation will immediately show that the resistance of this material to shock was reduced by approximately 88.5%.

To continue quoting:

> "In a boiler, heating takes place under service conditions with the result that the walls of a boiler previously subjected to compression are also subjected to heating, a condition which results in injury to the plate similar to that developed by improper riveting."

It is not a slight decrease in the power to absorb shock which is dangerous but a very pronounced brittleness, which results from various treatments, according to Baumann. It is therefore of great importance to conduct a research on a particular steel, involving both static and dynamic tests so that the results may be accurately correlated.

TENSILE STRENGTH

Descriptive

The chemical composition of the steel used in this investigation was:

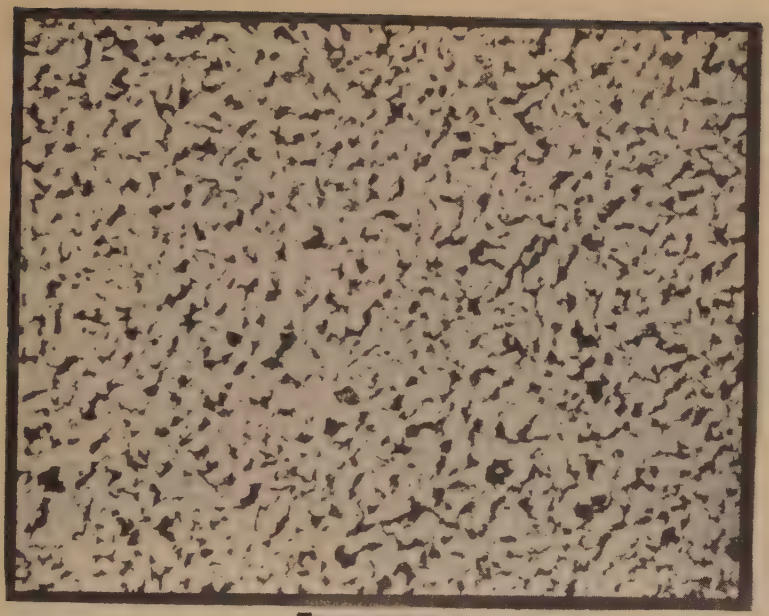
Manganese	0.89%	Sulphur	0.034%		
Carbon	0.22%	Phosphorous	0.014%	Silicon	0.05%

Although the chemical composition is an important factor in any research, the structural state is equally significant. Accordingly the steel, as received, was thoroughly annealed for one hour, prior to any form of cold work. Its structure, after being annealed, is shown in Figure 38.

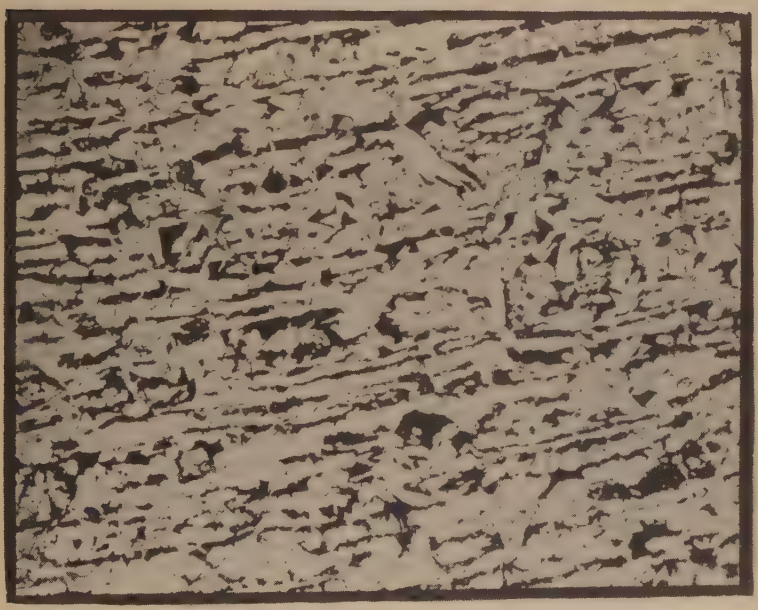
Tensile test pieces were shaped (Figure 34) and elongated cold in a tensile machine 4, 6, 8, 12, 16 and 20% respectively.

As the variables involved in heat treatment have a decided effect on results, a careful consideration of such factors becomes necessary in order to eliminate all possible errors. Thus, the "Hump" Leads and Northup electric furnace, used for all heat treatments from 200-500° C., was calibrated prior to any experiments. Preliminary experiments proved that specimens could be placed directly in the cold oven previously to heating it to the required temperature. After being subjected to heat at this temperature for one hour, the pieces were cooled in air. Those specimens heated at 100° C. were immersed in boiling water for one hour.

No attempt has been made to determine the elastic limit of this steel, as this property has been quite accurately studied by former investigators. The yield point, however, was measured by



Transverse



Longitudinal

Figure 38 Microsections (Longitudinal and Transverse) of 0.22% Carbon Steel after Being Annealed at 840° C. for One Hour. X - 250. Etched with Picric Acid.

TENSILE TEST SPECIMEN

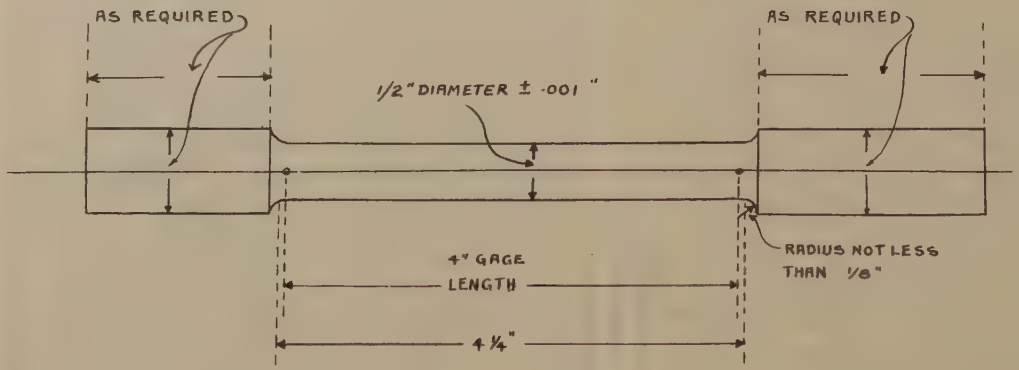


Figure 39

means of a Riehle gauge fastened to a four inch length. When the gauge pointer circled the scale divisions rapidly, the load for the yield point was read. Furthermore, the yield point was checked by observing the drop of the beam of the testing machine. The elongation was measured by using a pair of dividers, while the reduction of area was determined with micrometer calipers.

Discussion of Results.

In commercial testing of materials, the yield point is considered to be the stress at which an easily perceptible elongation occurs when the load is slightly increased. The yield point and the elastic limit should not be confused, as is frequently done in practice. The metallurgist places greater significance on the yield point than is expressed by the definition given above, for at the yield point structural changes occur in the material. When the yield point is reached the shear stresses are in excess of the elastic shearing strength of the material along certain planes and the material begins to yield very noticeably without any increase in load. Structurally, this feature is revealed by numerous slip lines in the crystals. By the time the yield point is reached, practically all the crystalline metal is plastically strained. After the metal has yielded to its maximum capacity, a higher load is required to break the specimen. This increased strength is a property imparted by overstrain or so-called cold working, and may be accounted for by Jeffries' and Archer's slip interference theory of hardness.

The yield point of 0.22% C. 0.89% Mn. steel can be raised by overstraining steel in tension, the greater the overstrain, the higher the yield point. (Figures 40-44). A slightly higher value is obtained for the yield point when the overstrain is followed by low temperature annealing. Regardless of the degree of cold work previously performed, a maximum value for the yield point was obtained by annealing the overstrained material at 200° C. As the annealing temperature was increased above 200° C. the yield point was lowered more and more rapidly with the increase in temperature. At about 500° C. the yield point approached that of annealed steel.

Reference to the curves shown in Figures 40-44 reveals the following features.

As the percentage of cold work by elongation increased, the gap between the yield point (attained at a 200° C. anneal) and the

ultimate strength decreased and finally at 14% overstrain, disappeared entirely (Figure 45). The significance of the elimination of the yield point is fully discussed in the following pages.

Dr. Ludwik* has pointed out that the yield point and elastic limit may be raised or lowered within wide limits by heat treatment. In the case of mild steel he claims that this is brought about by structural change. Although a structural change in the material may be essential for lowering the yield point, the present investigation demonstrates that the yield point can be raised without changing the material structurally. Rees[31] found that the yield point is raised its maximum amount by annealing 0.04 and 0.85% carbon steel, cold worked 8.1 and 14.8% respectively at 300° C. Korber[22], on the other hand, observed that on annealing at 650° C. cold worked 0.08% carbon steel the yield point was lowered from one-half to one-quarter of its original value. In this case Ludwik's requirement was satisfied, that is a complete structural change (recrystallization) occurred. In fact an examination showed a coarse grained structure; therefore, if the structural change factor is ignored, evidence points to the fact that the yield point of cold worked steels is elevated by annealing at low temperatures. This feature appears to be true for alloy steels also. Although the increase in the yield point value is slight, reaching a maximum at approximately 315° C., it nevertheless was raised.

This investigation, on the other hand, demonstrated that a maximum yield point value was found for 0.22% carbon steel after annealing at 200° C. (Figure 46), and further that when steel was annealed above 200° C. a much lower value was obtained for the yield point.

In order to illustrate in a clear simple manner the effect on the yield point values of annealing subsequent to cold work, the three dimension diagram was constructed. (Figure 46.) Its advantage is readily apparent. By lining in the contour lines a top surface was formed, thus making it possible to pick off yield point values for intermediate degrees of cold work. Further inspection brings out the feature that annealing at 200° C. gives a maximum yield point for different degrees of cold work.

The ultimate tensile strength of a specimen is the maximum tensile load per unit of original area supported by the specimen during the test to destruction. The ultimate tensile strength for

*Ludwik, Metallurgist, P. 46 (1-2) 1925-1926.

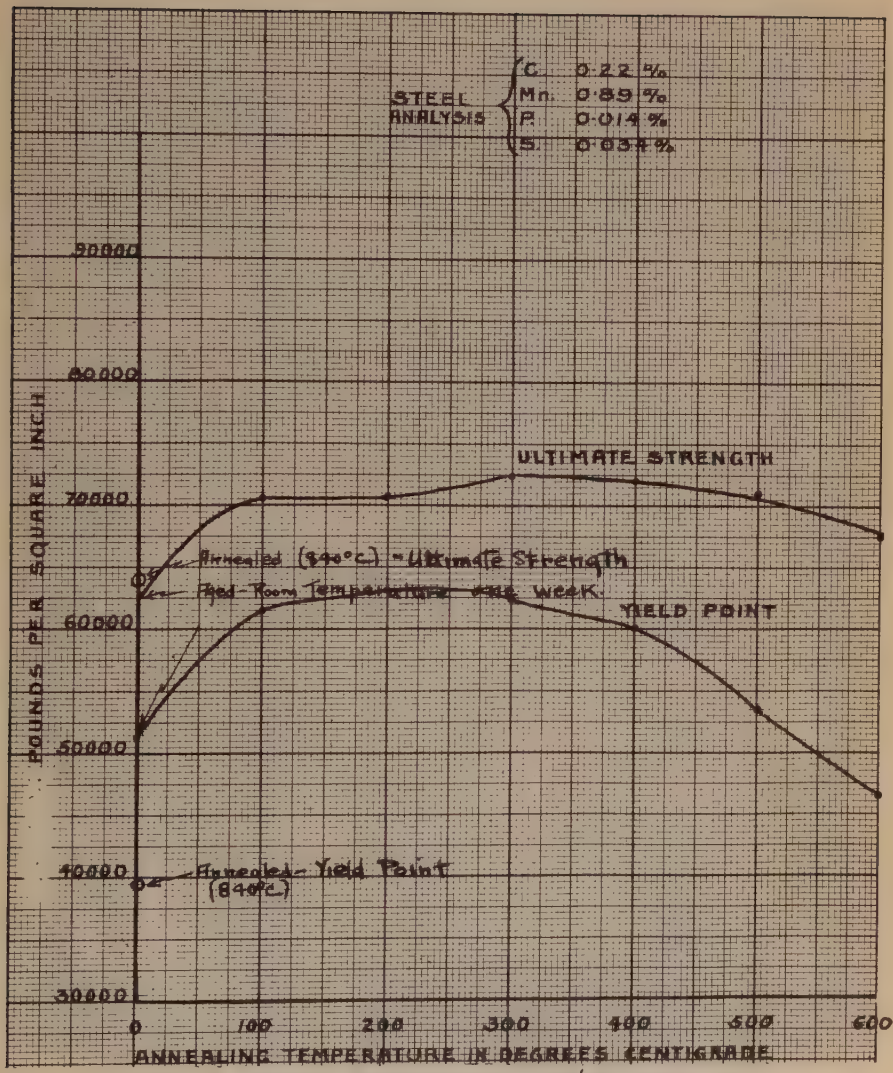


Figure 40 Tensile Properties of 0.22% C. Steel Cold Worked 4% Prior to Various Annealing Treatments.

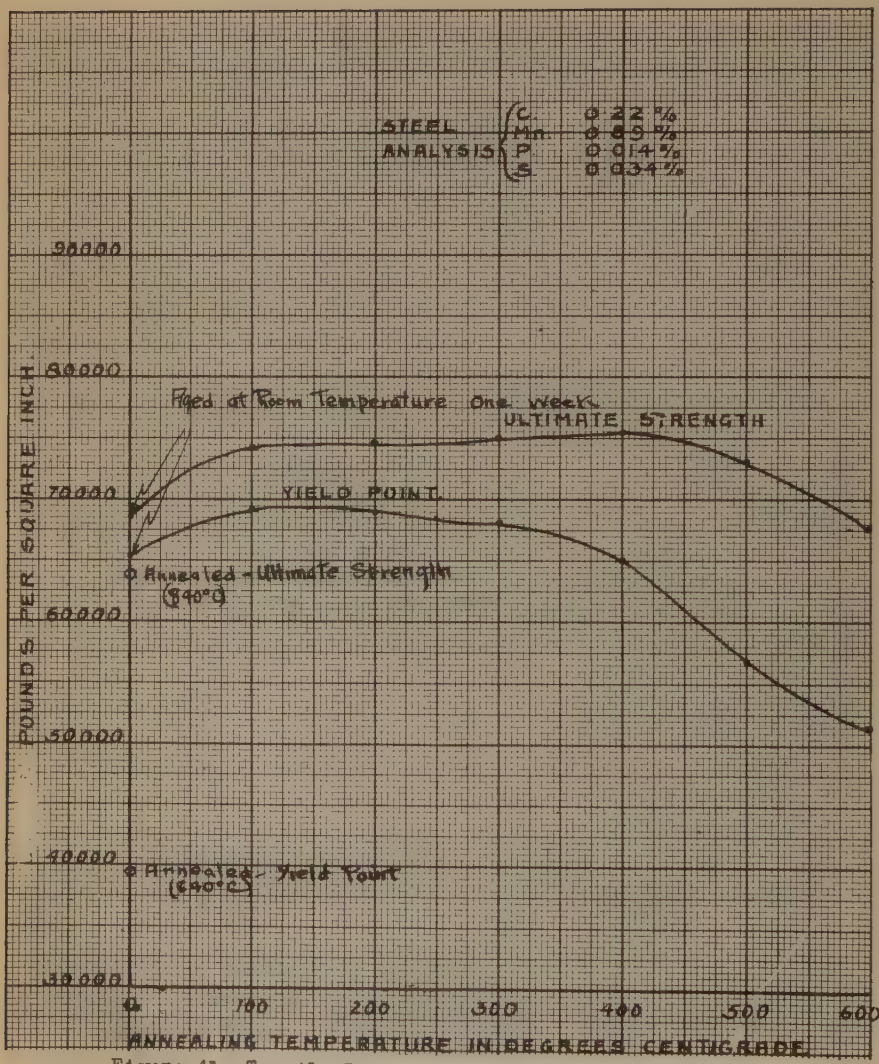


Figure 41 Tensile Properties of 0.22% C. Steel Cold Worked 6% Prior to Various Annealing Treatments.

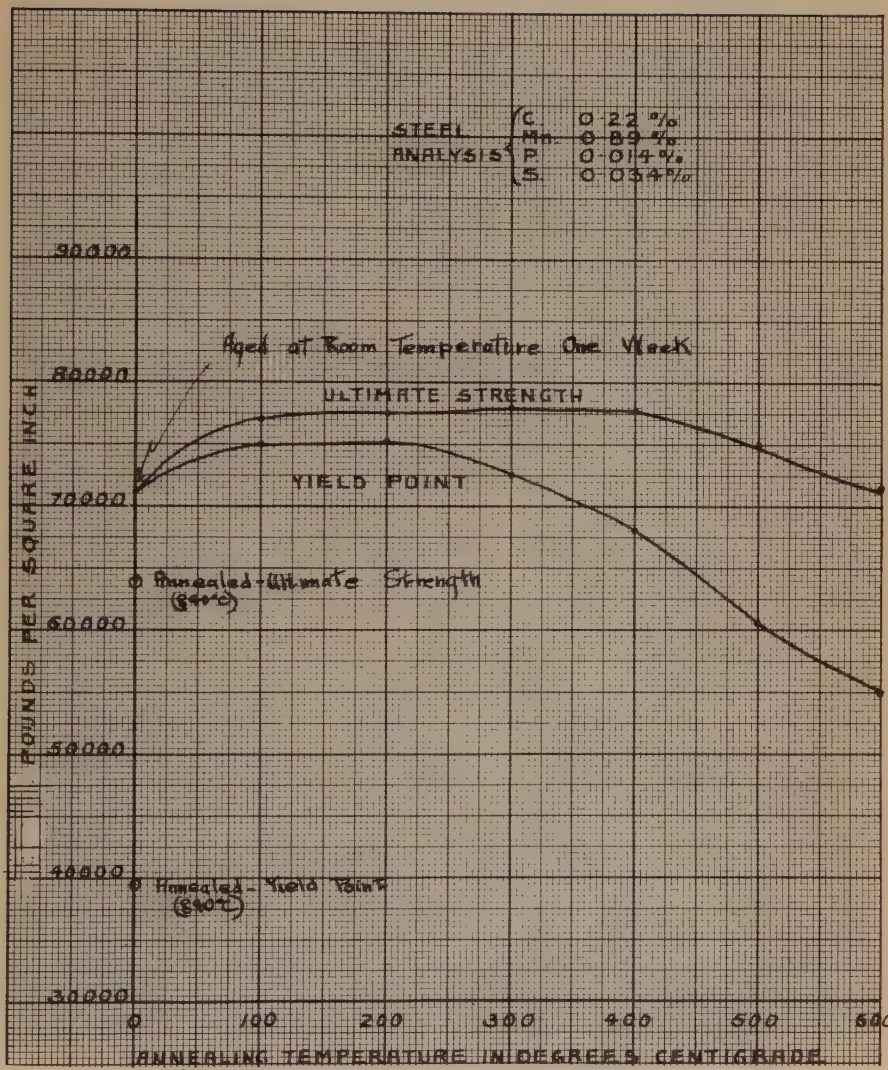


Figure 42 Tensile Properties of 0.22% C. Steel Cold Worked 8% Prior to Various Annealing Treatments.

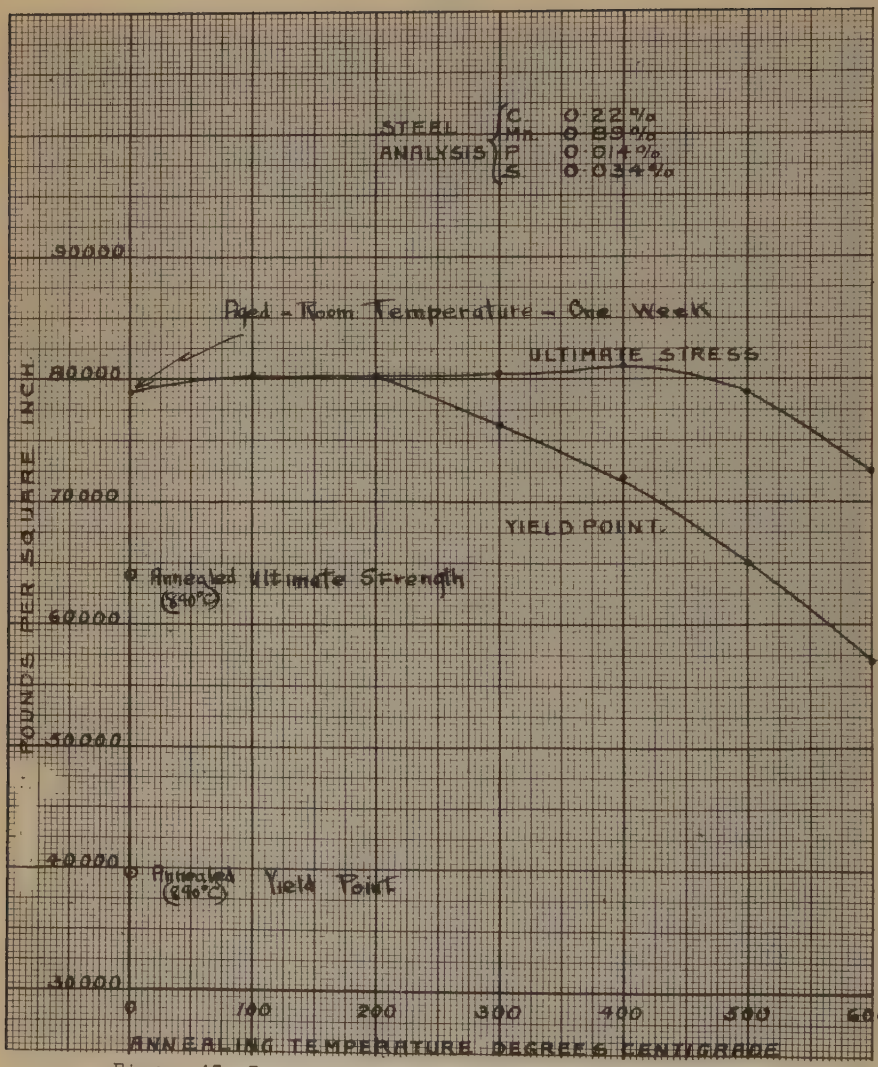


Figure 43 Tensile Properties of 0.22% C. Steel Cold Worked 12% Prior to Various Annealing Treatments.

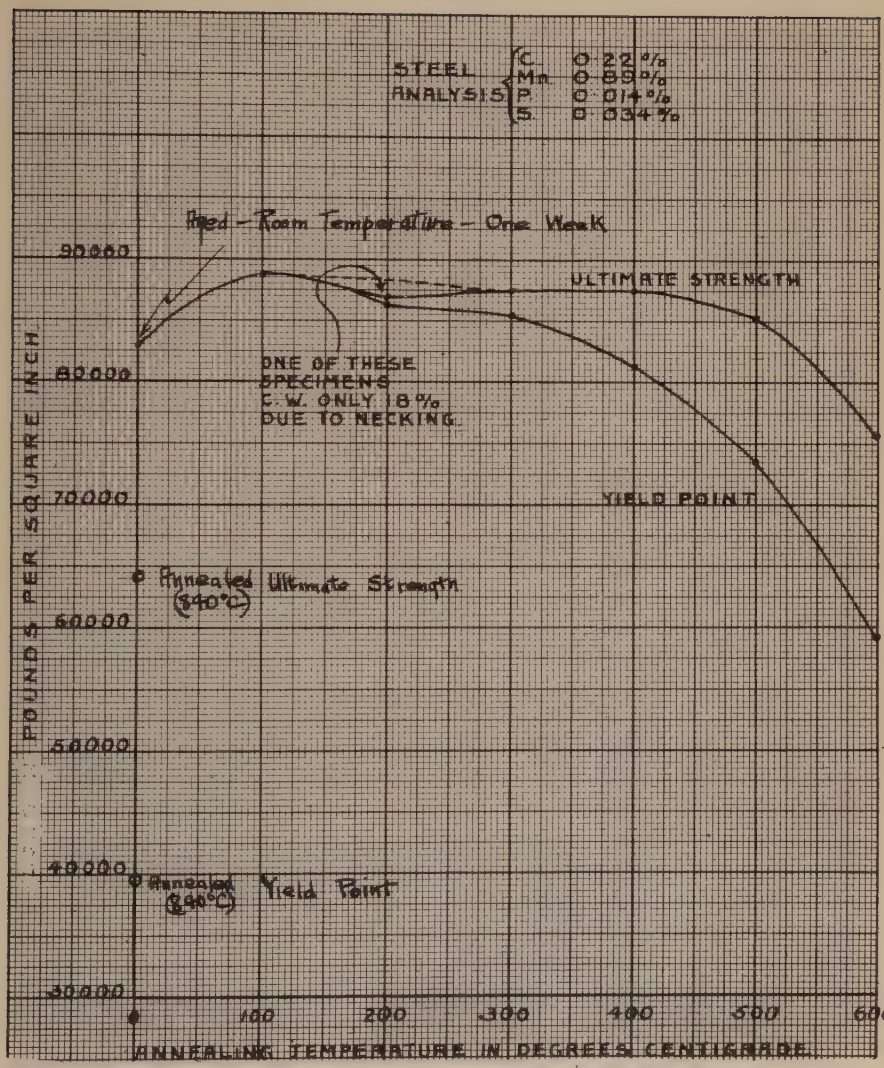


Figure 44 Tensile Properties of 0.22% C. Steel Cold Worked 20% Prior to Various Annealing Treatments.

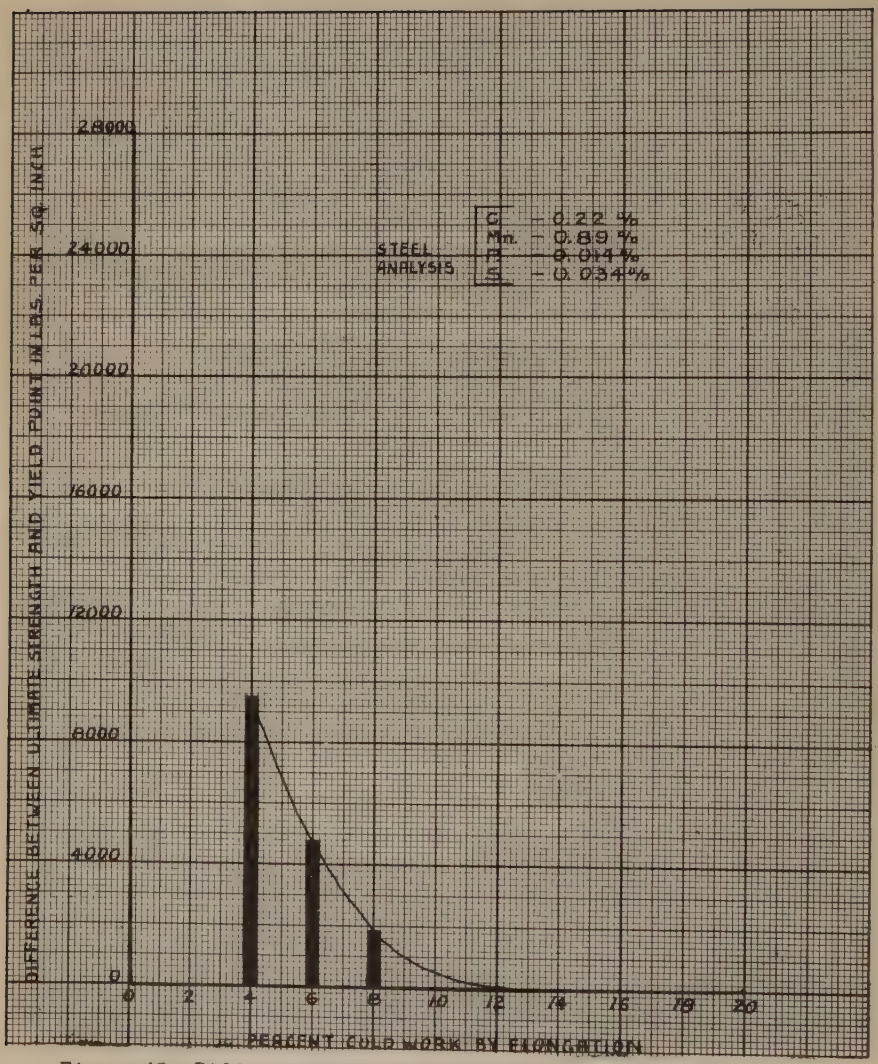


Figure 45 Difference Between Ultimate Strength and Yield Point Due to Various Degrees of Cold Work Followed by Annealing at 100° C.

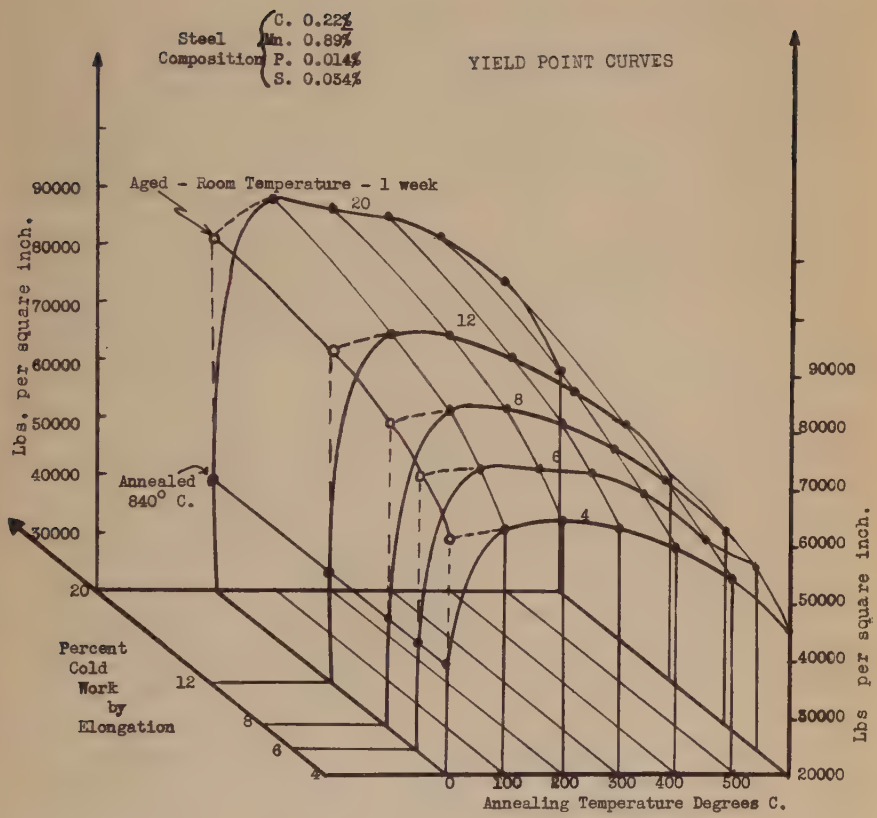


Figure 46 Tensile Properties of 0.22% C. Steel Cold Worked Different Degrees Followed by Annealing

this steel cold worked 4 and 8% reached its maximum value on annealing at 300° C. (Figures 40-42). The same steel cold worked 6 and 12% developed its highest tensile strength when annealed at 400° C. (Figures 41-43). The tensile strength for this steel, determined after annealing at 400° C., was but slightly in excess of the figure found at 300° C. Annealing beyond 400° C. rapidly lowered the tensile strength.

Figure 47 is a composite drawing showing the effect of subjecting the steel under investigation to the various conditions mentioned. Tensile strength values for intermediate degrees of cold working may be readily obtained from the diagram, which also shows that the tensile strength rises rapidly by annealing even in boiling water (100° C.) and then increases slightly up to an annealing temperature of 300-400° C. Above 400° C. the tensile strength falls off.

Reduction of area as well as elongation of tensile specimens are considered measures of ductility. Reduction of area is the local contraction at the point of fracture expressed in per cent, based on the original area. Elongation is the per cent change in length at rupture based on the original length. Although Dr. Ludwik[77] theoretically regards the reduction of area a better quantitative method for measuring ductility, actual measurement, however, tends one to accept the fact that in practice a measurement based on elongation involves less error. This is particularly true if the material is homogeneous so that local and frequent contractions along the gauge length are eliminated. Furthermore, a loss of approximately 0.001 in. in reading the diameter is to be avoided Because of these considerations, per cent change in length based on each new length after cold work was plotted for the curves showing ductility (Figure 48).

The curves (Figure 49) show that the minimum elongation for steel cold worked 4, 6 and 20% is obtained when annealed at 200° C., whereas the same steel cold worked 8 and 12% developed a minimum elongation when annealed at 100° C. In all cases annealing above 300° C., rapidly increased the elongation.

The ductility of steel was also investigated by Bauer[3] and [4]. In 1916, while studying the effect of annealing at low temperature on 0.29% carbon steel cold worked 12%, he determined that a minimum value for ductility occurred when the material was annealed at 100° C. On the other hand, Rees[31] in 1923 discovered that

whenever 0.04 and 0.85% carbon steels, cold worked 14.1 and 8.1% respectively, were annealed at 200° C., minimum ductility resulted. Both investigators observed that annealing slightly above 300° C. rapidly increased the ductility. Similar results were obtained in this research.

Reasons have already been given why the values obtained from the reduction of area were not plotted in the form of a curve. The errors involved are too important. In fact, this feature is particularly apparent in studying the curves of Bauer[3] and [4] and Rees[31].

If both elongation and reduction of area are measures of ductillity, any change in this property should be reflected in both. This should be especially true where a decided change occurs at some particular point.

A study of Bauer's[3] and [4] and Rees'[31] curves disclose that this condition does not occur. For instance, Rees determined that for 0.04% carbon steel cold worked (14.1%), a minimum value for elongation after annealing at 200° C. was obtained, whereas the reduction of area revealed it after a 300° C. anneal A still different result was obtained by Bauer when he found that 0.28% carbon steel, cold worked approximately 12%, showed minimum elongation after annealing at 100° C. Korber and Dreyer[23] concluded however, that 0.4 0.20, and 0.08% carbon steels cold worked 10% were least ductile when annealed at 200° C.

Results

The specific results derived from the tension tests may be summarized as follows:

1. Annealing at a temperature from 0-600° C. 0.22% C.—0.89% Mn. steel, cold worked by elongation 4, 6, 8, 12 and 20% alters some of its physical properties.
2. The ultimate strength is raised, attaining a maximum after annealing at 300° C. to 400° C. Higher annealing temperatures lowered its strength until it approached that for soft annealed steel.
3. The yield point is raised by annealing at low temperatures, the maximum yield point in all cases was reached when annealed at 200° C. Annealing above 300° C. lowered the yield point value rapidly.

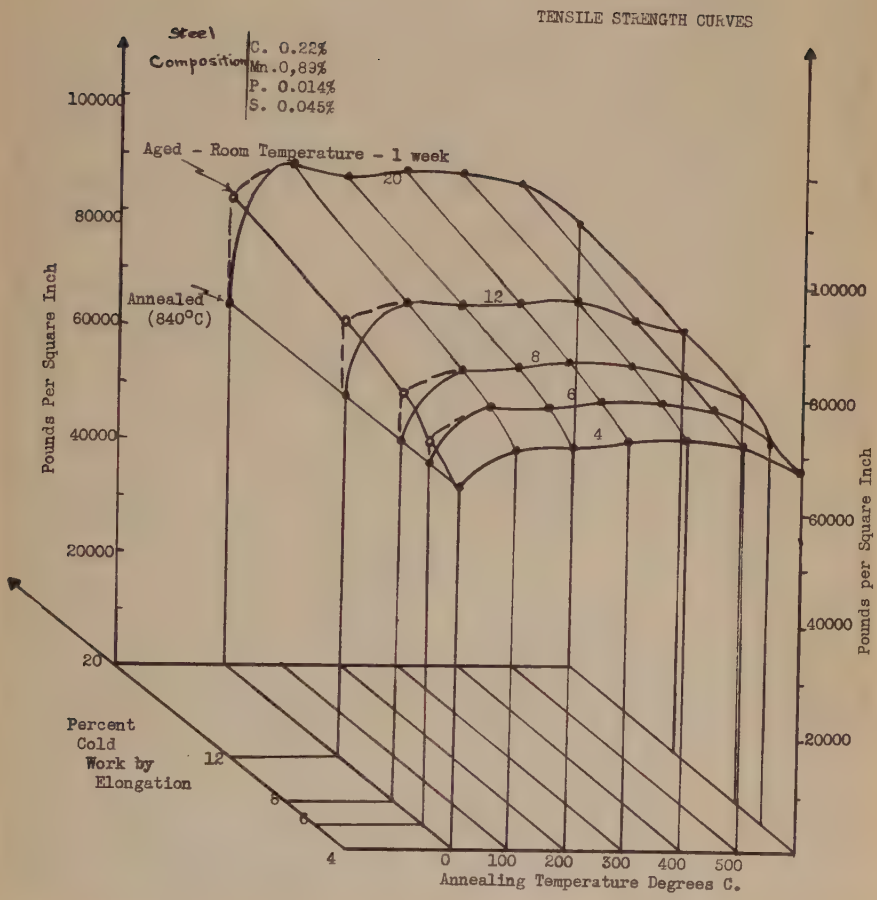


Figure 47 Tensile Properties of 0.22% C. Steel Cold Worked Different Degrees Followed by Annealing Treatments

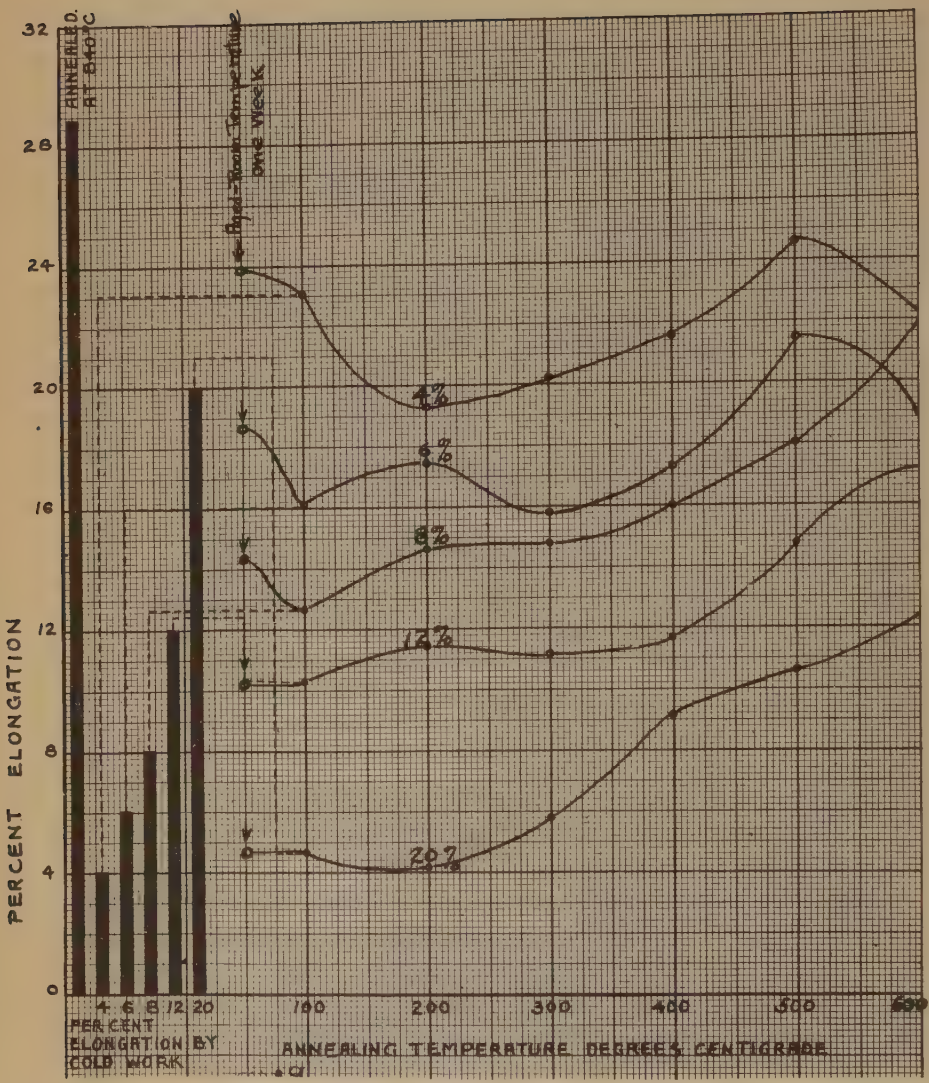


Figure 48 Tensile Tests on 0.22% Carbon Steel Cold Worked by Elongation 4, 6, 8, 13 and 20% Followed by Various Annealing Treatments.

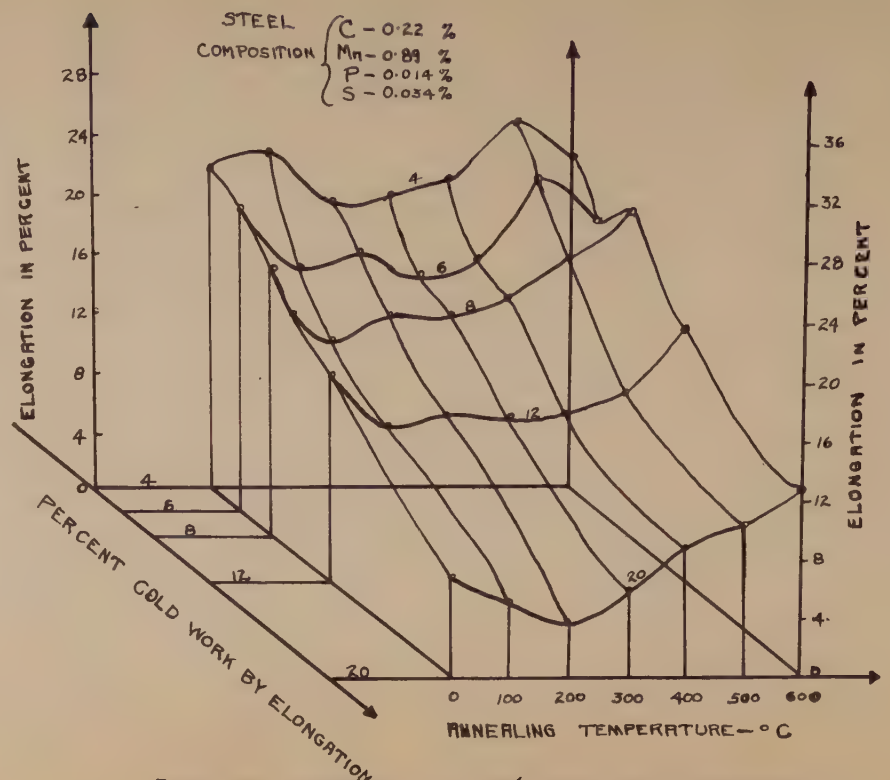


Figure 49 Elongation of 0.22% Carbon Steel Cold Worked Different Degrees Followed by Annealing Treatments.

TENSILE TESTS.

Table II

SPECIMEN NO.	% C.W. BY ELONGATION ON 4" GAUGE LENGTH	HEAT TREATMENT AFTER COLD WORK	DIAMETER AFTER COLD WORK	AREA AFTER COLD WORK	RED. OF AREA AFTER COLD WORK	% RED. OF AREA AFTER COLD WORK	DIAMETER AT THE FRACTURE	AVERAGE DIAMETER AT FRACT.	AVERAGE AREA AT FRACTURE IN SQ. INCHES	AVERAGE RED. OF AREA AT FRACTURE	PERCENT AREA REDUCTION AFTER TEST	ELONGATION AFTER COLD WORK	ELONGATION AFTER TEST IN INCHES	AVERAGE ELONG. AFTER TEST	CHANGE IN ELONGATION BY TEST IN INCHES	% CHANGE IN ELONGATION BY TEST.	YIELD POINT IN LBS.	AVERAGE YIELD POINT IN LBS.	AVERAGE YIELD POINT IN LBS/SQ".	ULTIMATE STRENGTH IN LBS.	AVERAGE ULTIMATE STRENGTH IN LBS.	AVERAGE ULTIMATE STRENGTH IN LBS./SQ."	AVERAGE ULTIMATE STRENGTH IN LBS./SQ." BASED ON AREA AT THE FRACTURE.
1	0	Annealed at 840° C. for one hour					0.31"		0.075	0.125	64.5		28.9%				7940		39700	12800			64000	
2	0																				13560	13555	70500	169500
5 - 6	4 %	100° C. Boil. H_2O	0.492"	0.192	0.008	4%	0.320 0.320	0.320	0.080	0.112	58.4	0.16"	1.14 1.10	1.12"	0.96	23.1	12060 11520	11790	61500	13550	13550	13555	70500	169500
7 - 8	"	200 " Elec. Furnace	"	"	"	"	0.300 0.300	0.300	0.071	0.121	63.2	"	0.96 0.97	0.965"	0.805	19.3	11940 12380	12160	63450	13560	13550	13555	70500	191000
9 - 10	"	300 " "	"	"	"	"	0.300 0.300	0.300	0.071	0.121	63.2	"	0.98 1.00	0.99"	0.83	20.2	12010 11810	11910	62000	14000	13790	13695	72300	195800
11 - 12	"	400 " "	"	"	"	"	0.300 0.300	0.300	0.071	0.121	63.2	"	1.03 1.10	1.065"	0.905	21.6	11710 11270	11490	59900	13900	13800	13650	72200	192200
13 - 14	"	500 " "	"	"	"	"	0.300 0.300	0.300	0.071	0.121	63.2	"	1.13 1.04	1.185"	1.025	24.6	10170 10200	10185	53000	13710	13620	13665	71800	192500
17 - 18	6 %	100°C. Boil. H_2O	0.489"	0.188	0.012	6 %	0.320 0.300	0.310	0.075	0.113	60.3	0.24"	0.91 0.93	0.92"	0.68	16.1	13040 13070	13055	69350	13840	14000	13920	74100	185900
19 - 20	"	200 " Elec. Furnace	"	"	"	"	0.300 0.300	0.300	0.071	0.117	62.3	"	0.97 1.00	0.985"	0.745	17.5	12930 12910	12920	68800	14020	14020	14020	74600	197800
21 - 22	"	300 " "	"	"	"	"	0.320 0.320	0.320	0.080	0.108	57.4	"	0.90 0.92	0.91"	0.67	15.8	12830 12820	12825	68150	14130	14120	14125	75200	176900
23 - 24	"	400 " "	"	"	"	"	0.310 0.300	0.305	0.073	0.115	61.2	"	0.95 1.00	0.975"	0.735	17.3	12070 12310	12190	64830	14240	14210	14225	75700	195100
25 - 26	"	500 " "	"	"	"	"	0.300 0.300	0.300	0.071	0.117	62.3	"	1.18 1.04	1.10"	0.86	21.5	10550 10820	10685	56800	13860	13750	13780	73300	194000
29 - 30	8 %	100°C. Boil. H_2O	0.485"	0.185	0.015	7.5%	0.320 0.320	0.320	0.080	0.105	56.8	0.32"	0.92 0.82	0.87"	0.55	12.7	13770 13910	13840	75000	14130	14330	14230	76900	178000
31 - 32	"	200" Elec. Furnace	"	"	"	"	0.310 0.300	0.305	0.073	0.112	60.6	"	0.93 0.98	0.955"	0.635	14.6	14150 13660	13905	75300	14420	14170	14295	77200	195900
33 - 34	"	300 " "	"	"	"	"	0.300 0.300	0.300	0.071	0.114	61.7	"	0.98 0.94	0.96"	0.64	14.8	13460 13460	13460	72800	14450	14380	14415	78000	201600
35 - 36	"	400 " "	"	"	"	"	0.300 0.300	0.300	0.071	0.114	61.7	"	1.04 0.98	1.01"	0.69	16.0	12380 12630	12505	67600	14210	14530	14370	77700	201100
37 - 38	"	500" "	"	"	"	"	0.300 0.300	0.300	0.071	0.114	61.7	"	1.13 1.14	1.135"	0.615	18.7	10900 11470	11185	60500	13650	13910	13880	75000	195500
41 - 42	12 %	100°C. Boil. H_2O	0.479"	0.180	0.020	10%	0.320 0.320	0.320	0.080	0.100	55.6	0.48"	0.96 0.92	0.94"	0.46	10.3	14390 14440	14415	80150	14390	14440	14415	80100	180500
43 - 44	"	200 " Elec. Furnace	"	"	"	"	0.300 0.310	0.305	0.073	0.107	59.5	"	1.00 0.98	0.99"	0.51	11.4	14540 14330	14435	80350	14610	14330	14470	80400	198200
45 - 46	"	300 " "	"	"	"	"	0.320 0.320	0.320	0.080	0.100	55.6	"	0.98 0.98	0.98	0.50	11.1	13680 13790	13735	76400	14560	14480	14520	80700	181700
47 - 48	"	400 " "	"	"	"	"	0.300 0.320	0.310	0.075	0.105	58.3	"	1.00 1.00	1.00	0.52	11.6	13220 12800	13010	72350	14560	14670	14610	80300	195700
49 - 50	"	500 " "	"	"	"	"	0.310 0.300	0.305	0.073	0.107	59.5	"	1.10 1.19	1.145"	0.665	14.8	11630 11700	11665	64900	14350	14050	14200	78900	194800
53 - 54	20%	100°C. Boil. H_2O	0.455"	0.163	0.037	18.5%	0.310 0.310	0.310	0.075	0.088	54.0	0.80	1.03 1.01	1.02"	0.22	4.6	14490 14460	14475	86700	14490	14460	14475	86700	193100
55 - 56	"	200 " Elec. Furnace	"	"	"	"	0.310 0.320	0.315	0.077	0.085	52.2	"	0.89 1.11	1.00"	0.20	4.2	14070 14140	14105	86500	14070	14140	14105	86600	182800
57 - 58	"	300 " "	"	"	"	"	0.320 0.320	0.320	0.080	0.083	51.0	"	1.08 1.08	1.08"	0.28	5.8	13910 13980	13945	85600	14340	14290	14315	87900	179300
59 - 60	"	400 " "	"	"	"	"	0.325 0.325	0.325	0.083	0.080	49.0	"	1.22 1.26	1.24"	0.44	0.2	13250	13250	81330	14240	14330	14285	87500	171700
61 - 62	"	500 " "	"	"	"	"	0.310 0.310	0.310	0.075	0.088	54.0	"	1.30 1.38	1.34"	0.01	10.6	12100 11810	11955	73300	13940	13900	13920	85400	186000

TABLE II - TENSILE TESTS

Specimen Number	Diameter Before Elong.	Diameter After Elong.	Cold Work By Elong.	Area Before Elong.	Area After Elong.	Load in Lbs. Required To Give Cold Work	Yield Point in Lbs.	Yield Point in Lbs./Sq."	Ultimate Tensile Strength in Lbs.	Ultimate Tensile Strength in #/Sq."	Fracture Style	Elongation in Inches	Elongation %	Diameter At Fracture in Inches	Area At Fracture In Sq."	Area-Reduction In Square Inches	Area-Reduction %	Remarks
4'	.507	.500	4%	.202	.196	9850	11080	51400	13280	62700	Cup	1.00	24	.306	.074	.122	62.2	All of these specimens were aged for 1 week after cold work before testing.
6'	.504	.491	6%	.200	.189	11300	12350	65300	12990	68600	1/2 Cup	.80	18.9	.296	.069	.120	63.5	
8'	.505	.485	8%	.200	.185	12030	13170	71100	13170	71100	1/2 Cup	.62	14.35	.300	.071	.114	61.6	
12'	.505	.470	12%	.200	.173	12600	13660	78900	13660	78900	1/2 Cup	.45	10.05	.307	.074	.099	57.2	
20'	.505	.461	20%	.200	.167	13290	13880	83000	13880	83000	3/4 Cup	.22	4.6	.307	.074	.093	55.7	
14'	.508	.500	4%	.203	.196	10220	9110	46500	13230	67500	1/2 Cup	.94	22.6	.299	.070	.126	64.3	All of these specimens were annealed at 600°C. for 1 hour in the Leeds & Northrup Electric Furnace prior to testing.
16'	.508	.492	6%	.203	.190	11170	9820	51700	12900	67800	Cup	.80	18.9	.304	.073	.117	61.6	
18'	.507	.487	8%	.202	.186	12330	10220	55000	13310	71700	Cup	.97	22.2	.304	.073	.113	60.8	
112'	.505	.475	12%	.200	.177	12790	10100	57100	13060	73800	1/2 Cup	.77	17.4	.300	.071	.106	59.8	
120'	.505	.458	20%	.200	.165	12090	9780	59300	12470	75500	Cup	.60	12.5	.302	.072	.093	56.4	

Remarks:- In the case of the specimens cold worked 8, 12 and 20% prior to aging, no yield point was noticeable by the drop of the beam.

4. The ductility as measured by per cent elongation indicated minimum values after annealing in the temperature range of 100-200° C. Ductility was greatly improved by annealing above 300° C.

ROCKWELL HARDNESS TESTS

Descriptive

The Rockwell hardness tests were performed on tension test pieces cold worked by elongation 4, 6, 8, 12, and 20%, followed by annealing at low temperatures (100, 200, 300, 400, 500 and 600° C.) A 1-16 mm. diameter ball with a load of 100 Kg. was used and six readings within the gauge length of each specimen were made. The averages of these readings are tabulated in table III.

Discussion of Results

Examination of figures shows that aging cold worked steel at room temperature for one week increases the hardness. The relative increase of hardness caused by aging steel cold worked from 4% to 8% at room temperature is greater than that for steel cold worked from 8 to 20 per cent. (Figures 50-54.) Annealing at low temperatures slightly increases this hardness and here again it is seen that the most pronounced effect is exhibited by the steels cold worked from 4 to 8 per cent. (Figures 50-52). The maximum hardness of all these steels was found after annealing at 200° C. In the majority of cases, however, the hardness found after annealing at 200° C. was only slightly greater than that obtained by aging the cold worked steels at room temerature for one hour. Although annealing at a temperature higher than 500° C. is necessary before an appreciable fall in hardness is produced the trend of the curves show that annealing slightly higher than 600° C. will produce a decided drop in hardness. These curves also show that the greater the degree of cold work, the greater was the tendency for the steel to retain the effects of cold working (Figure 55).

Comparison of Results with Those of Previous Investigators

Notwithstanding the fact that Ishigaki[17] determined that severely cold worked Armco iron and steel had their hardness increased by tempering (as he called this heat treatment), in the temperature range of 250-350° C., a decided softening occurred at 470° C. Similar conclusions were reported by Sauveur and Lee[36]. It therefore appears that 250-350° C. is the annealing temperature range within which very severely cold worked steel will be hard-

ened to a maximum degree. Although this was the best temperature range for hardness, 480-600° C. was found to be the most critical temperature range for softening these steels. In direct contrast to these results are those published by Edwards and Kuwada[8]. They determined that annealing cold rolled steels from 0 to 500° C. did not appreciably raise the hardness. As a matter of fact, the steels were softened when subjected to annealing treatments beyond 500° C.

In spite of these inconsistencies, the evidence supports the conclusions reached by Sauveur and Lee[36] rather than those by Edwards and Kuwada[8]. It follows from the curves (Figure 55) that whenever cold worked steel is annealed at 200° C., a maximum hardness results which remains practically constant even by annealing up to 400° C. After reaching this point, a softening of the steel follows.

Conclusions

In consequence of the Rockwell hardness experiments performed on 0.22% carbon steel, cold worked by elongation 4, 6, 8, 12, and 20% prior to annealing at low temperatures from 0 to 500° C., it may be stated that:

1. The hardness of 0.22% carbon steel, cold worked by elongation from 0 to 20%, can be further increased by annealing at low temperatures. A 200° C. anneal produces maximum hardness.
2. Greater hardness cannot be secured by annealing beyond 200° C. The hardness caused by annealing from 200° to 400° C. is practically a constant value.
3. A softening occurs by annealing beyond 400° C.
4. The per cent. increase in hardness caused by annealing steels cold worked from 0 to 10% is greater than that of steels which have been cold worked from 10 to 20% prior to annealing.
5. The retention of the effects of cold working is greater the greater the cold working.

COLD BEND TESTS

Resume of Previous Work

Bend testing has been employed to ascertain the brittleness of steel. Baumann[5] and Bauer[3] and [4] tested the brittleness of

TABLE III

ROCKWELL HARDNESS TESTS

Specimen No.	Cold Work Percent Elongation	Annealed 840°C	Untreated	Aged One Week	Annealing Treatments (Held at temperatures for one hour) 100°C	200°C	300°C	400°C	500°C	600°C
2	None	63.0								
3 4	4		70.0	74.6	74.5	76.5	76.5	75.8	73.0	68
15 16	6		72.0	88.3	76.5	77.5	77.0	72.0	75.0	70.0
27 28	8		74.0	75.6	78.0	80.0	79.0	80.5	78.0	72.0
39 40	12		79.0	80.3	80.5	83.0	82.0	83.0	81.5	76
2'	20		80.0	84.0	84.5	85.0	84.5	85.5	83.4	78.5

REMARKS Rockwell hardness values are the results of six readings on each bar. All bars annealed at 840°C for one hour prior to cold working by elongation in a tensile testing machine. 1/16" diameter steel ball - 100 Kg. load used.

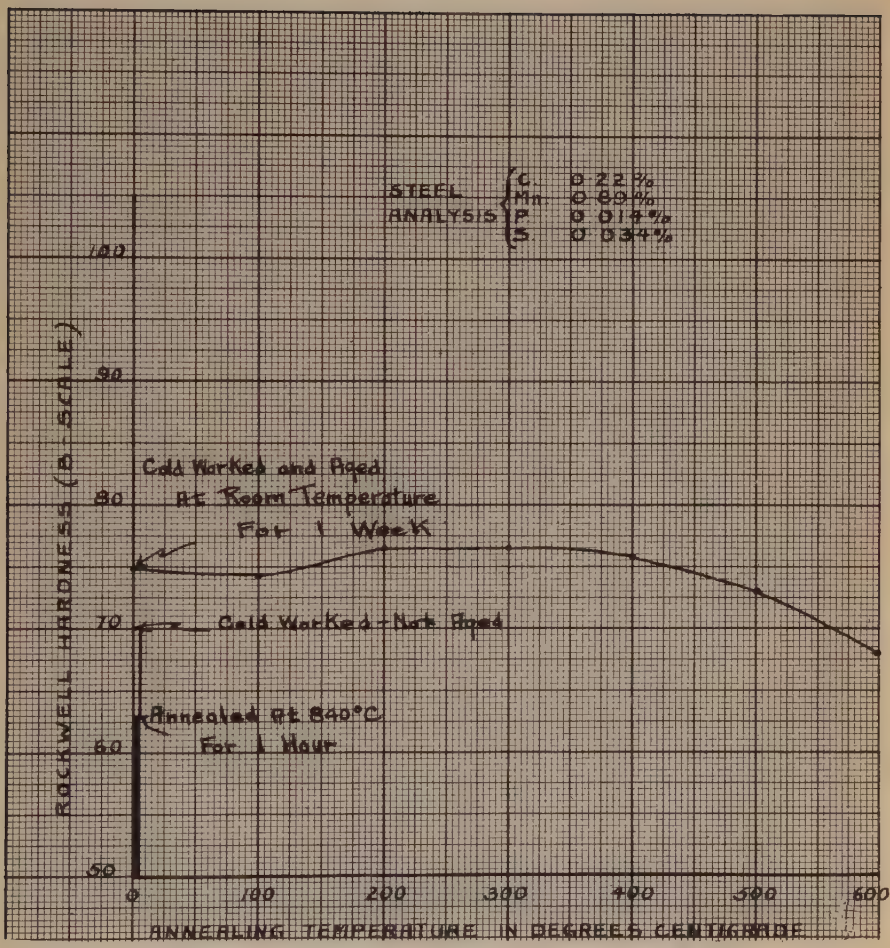


Figure 50 Rockwell Hardness of 0.22% C. Steel Cold Worked 4% Prior to Various Annealing Treatments.

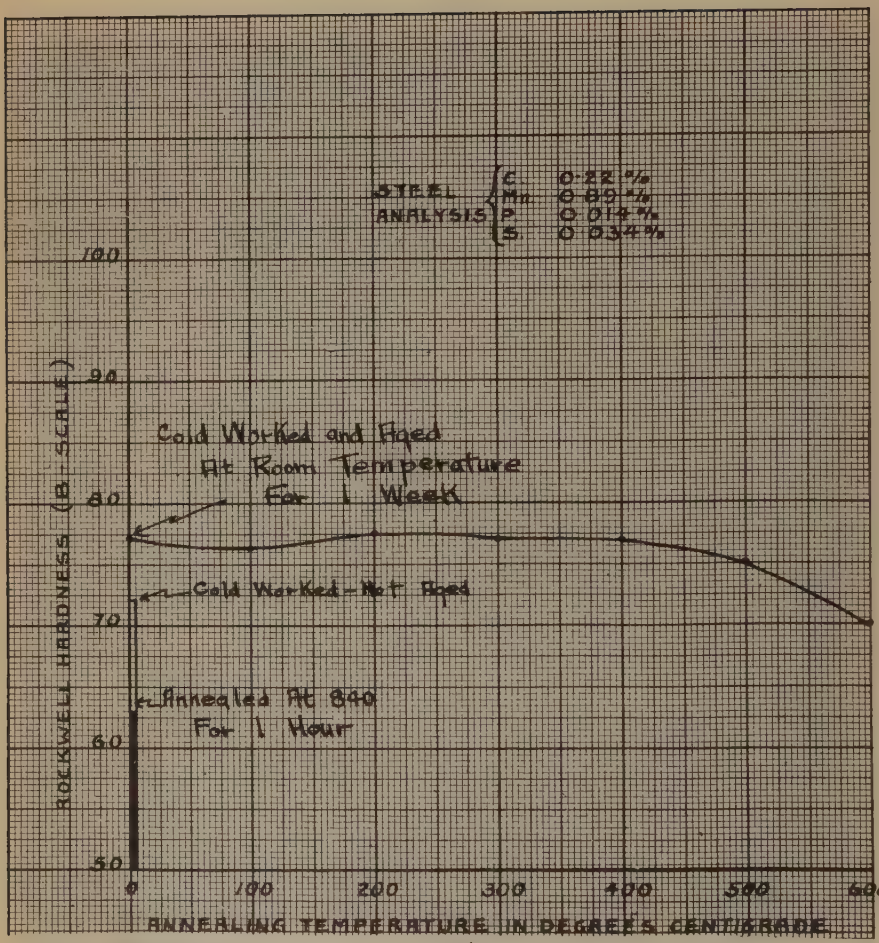


Figure 51 Rockwell Hardness of 0.22% C. Steel Cold Worked 6% Prior to Various Annealing Treatments.

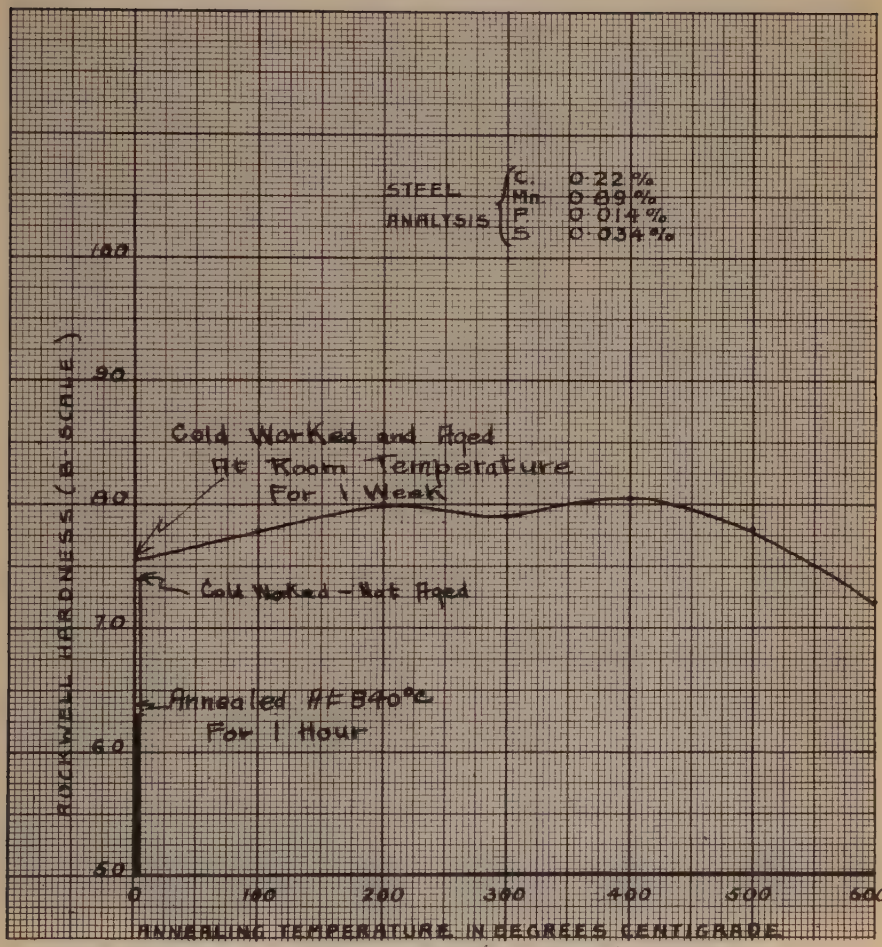


Figure 53 Rockwell Hardness of 0.22% C. Steel Cold Worked 8% Prior to Various Annealing Treatments.

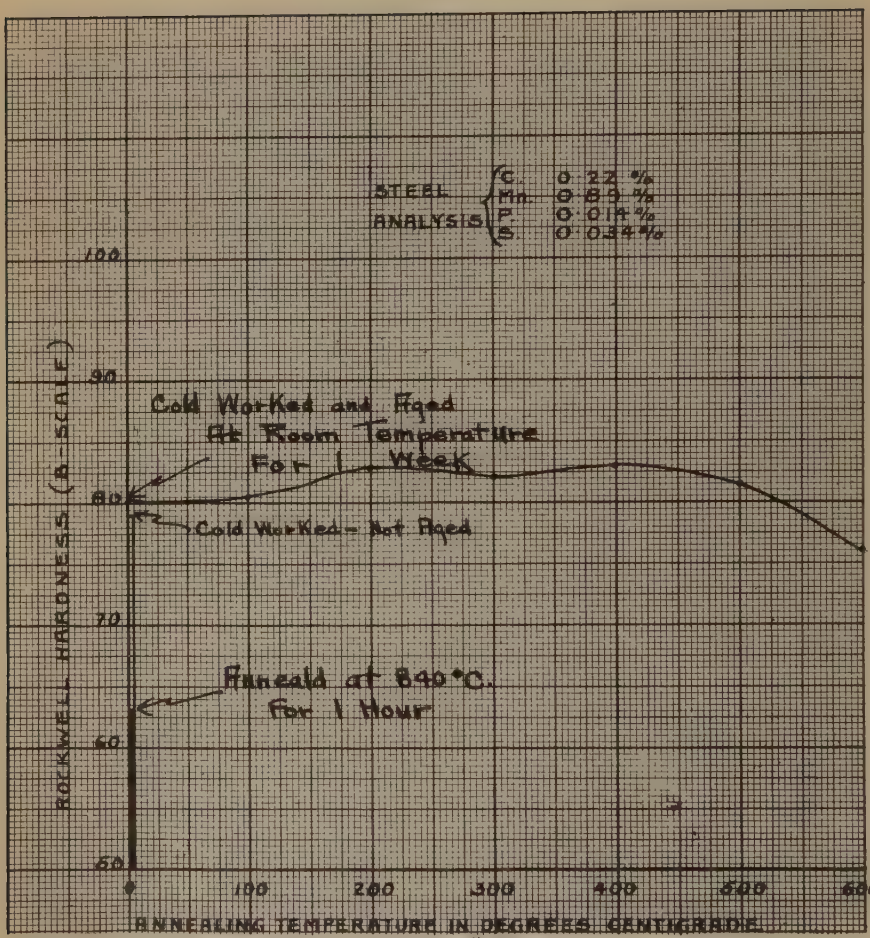


Figure 53 Rockwell Hardness of 0.22% C. Steel Cold Worked 13% Prior to Various Annealing Treatments.

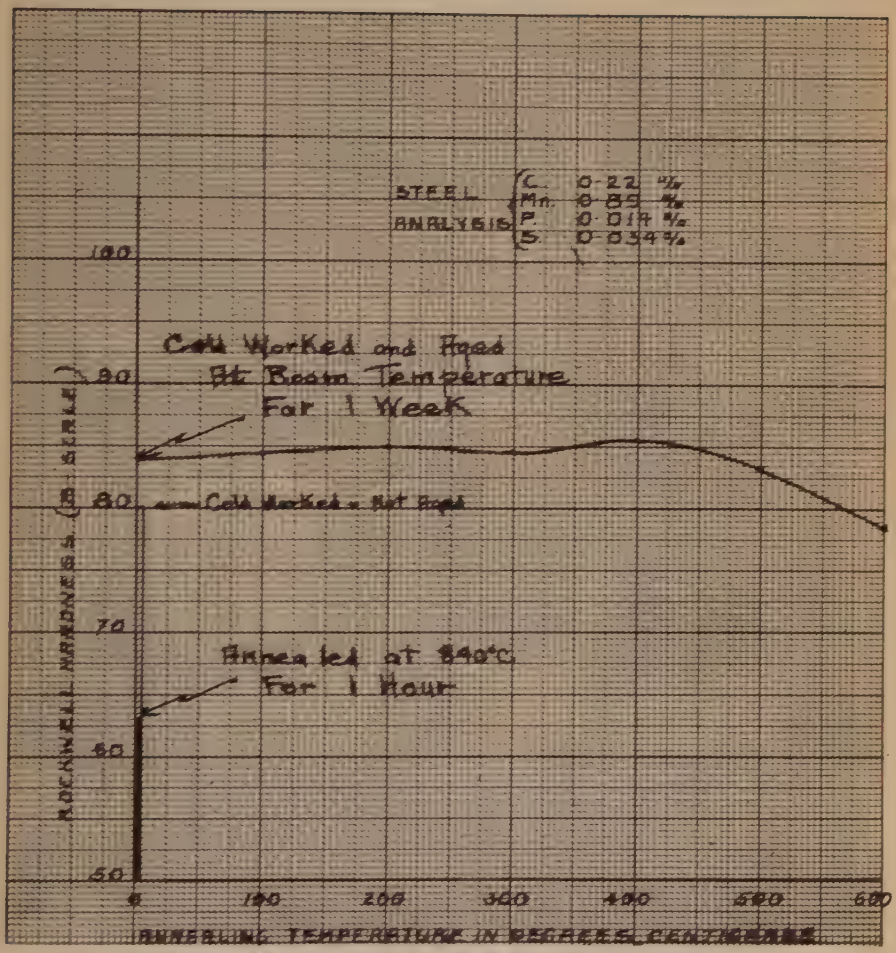


Figure 54 Rockwell Hardness of 0.22% C. Steel Cold Worked 20% Prior to Various Annealing Treatments.

annealed compressed steel by bending. Fettweis [10] as well as Mauer and Maitlander[26] used this method to determine whether cold worked steel became brittle at room temperature as well as at 300° C. Bend tests on wires were used by Adams[1] to determine their brittleness as well as by Goerens[15]. Fisher[11] on the other hand employed the bend test to determine when recrystallized steel became brittle.

Descriptive

Round bars of this 0.22% C. steel of the size shown in Figure 56, were used for cold bend tests. After being annealed for one hour, these bars were elongated cold 4, 8, 12, 16 and 20% by swaging and were then annealed at temperatures ranging from 0 to 500° C. for a period of one hour.

The tests were performed on a Riehle cold bend machine, using a 5-8 inch diameter mandrel. Each piece was turned through an angle of 180° in the bending operation.

Results of Cold Bend Tests

The results obtained from these bend tests were:

1. The results of bend tests proved to be a qualitative standard for measuring brittleness.
2. Material cold worked 8, 12, 16 and 20% followed by annealing at 200 and 300° C. developed cracks when bent around a 5-8 inch mandrel at an angle of 180°.
3. Annealing cold worked material above 300° C. did not impart brittleness to the steel.

Discussion of Results

The bend tests, as already mentioned, are but a qualitative measure of brittleness. It is known that whenever a substance becomes brittle, bending without cracking becomes difficult, and in fact in very brittle material bending causes fracture. The method of testing is of importance for speed, time and manner of test affects the results. For these reasons the bend tests were all performed under like conditions.

Table IV presents the results of the bend tests. It becomes apparent that brittleness, or a lowering in toughness, occurs when this steel is cold worked from approximately 8 to 20%, followed by annealing in the temperature range of 150 to 300° C. Anneal-

ing 0.22% carbon steel above 300° C. caused the steel to revert to the toughness possessed at room temperature, as judged by the appearance of the bent surface.

Figure 57 illustrates under what conditions this steel has its toughness reduced, as revealed by the bend test.

IMPACT RESISTANCE

Descriptive

The round steel bars used in these impact tests were fully annealed for one hour prior to any form of cold work. Various series of these bars were then subjected to cold working by swaging until the required percentages of deformation were obtained (4, 8, 12, 16 and 20%).

Each particular series was subsequently annealed for periods of one hour at temperatures ranging from room temperature to 500° C.

The test specimens were then shaped to the size shown in Figure 58. The latest type of Izod impact testing machine was utilized for breaking the pieces. Table V gives the figures obtained from these tests.

Results of Impact Tests

1. The impact resistance of 0.22%, C.-0.89% Mn. steel cold worked from 0 to 20% is lowered on annealing within the temperature range from 150 to 300° C. (Figures 59-63).
2. The lowest impact values for each series were obtained on annealing within the range of 200 to 250° C.
3. Steel cold worked from 4 to 12% attains its lowest impact resistance when annealed at 200° C., whereas steel cold worked from 12 to 20% is most brittle after being annealed at 250° C.
4. In all cases the impact resistance is comparatively high—the lowest value obtained being 61 foot-pounds.
5. Steel cold worked from 4 to 12% has its impact resistance lowered approximately 14% when annealed at 200° C.; steel cold worked from 12 to 20% when annealed at 250° C. has its impact strength reduced approximately 23%.

Discussion of Results:

The impact resistance of 0.22% C.-0.89% Mn. steel was found to be surprisingly high. This feature is attributed to the high

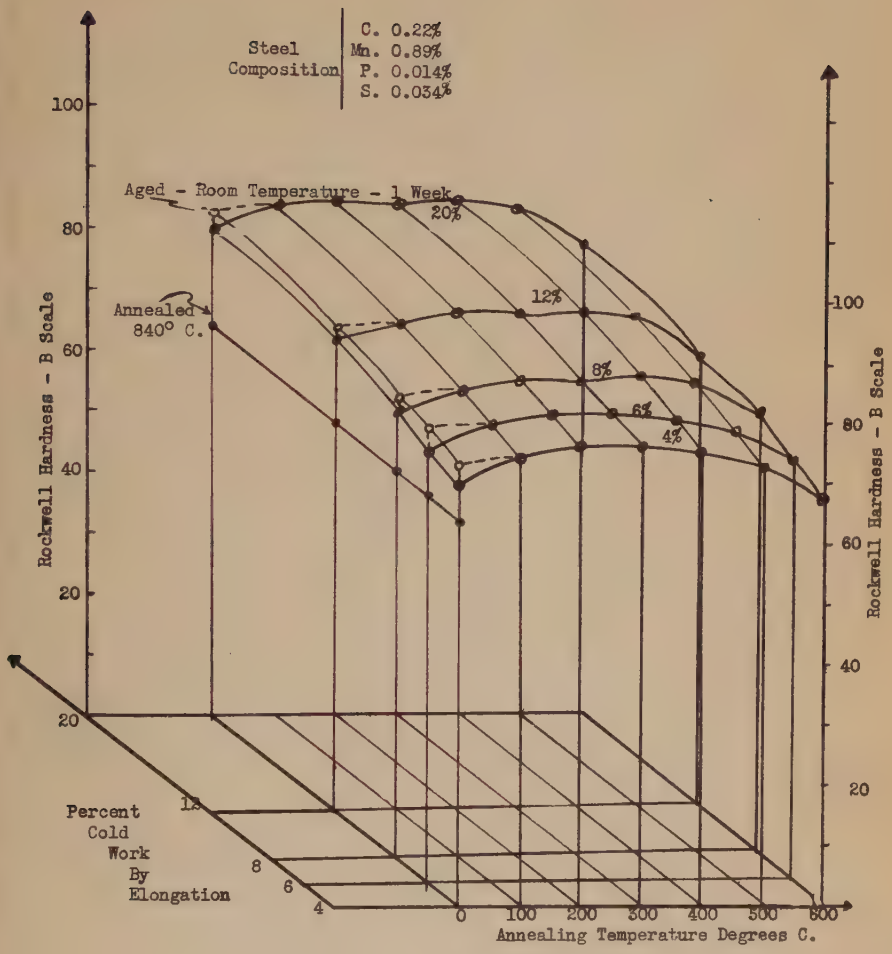


Figure 55 Rockwell Hardness of 0.22C. Steel Cold Worked Different Degrees and Annealed

BEND TEST SPECIMEN.

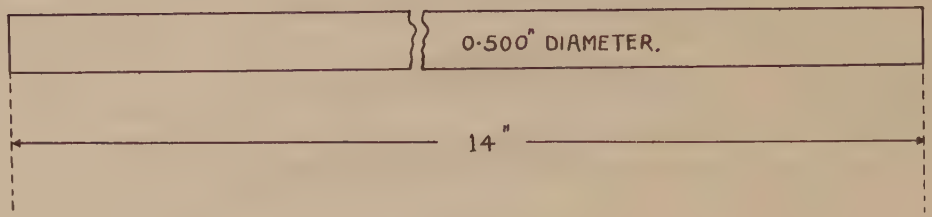


Figure 56

Figure 57 Bend Tests

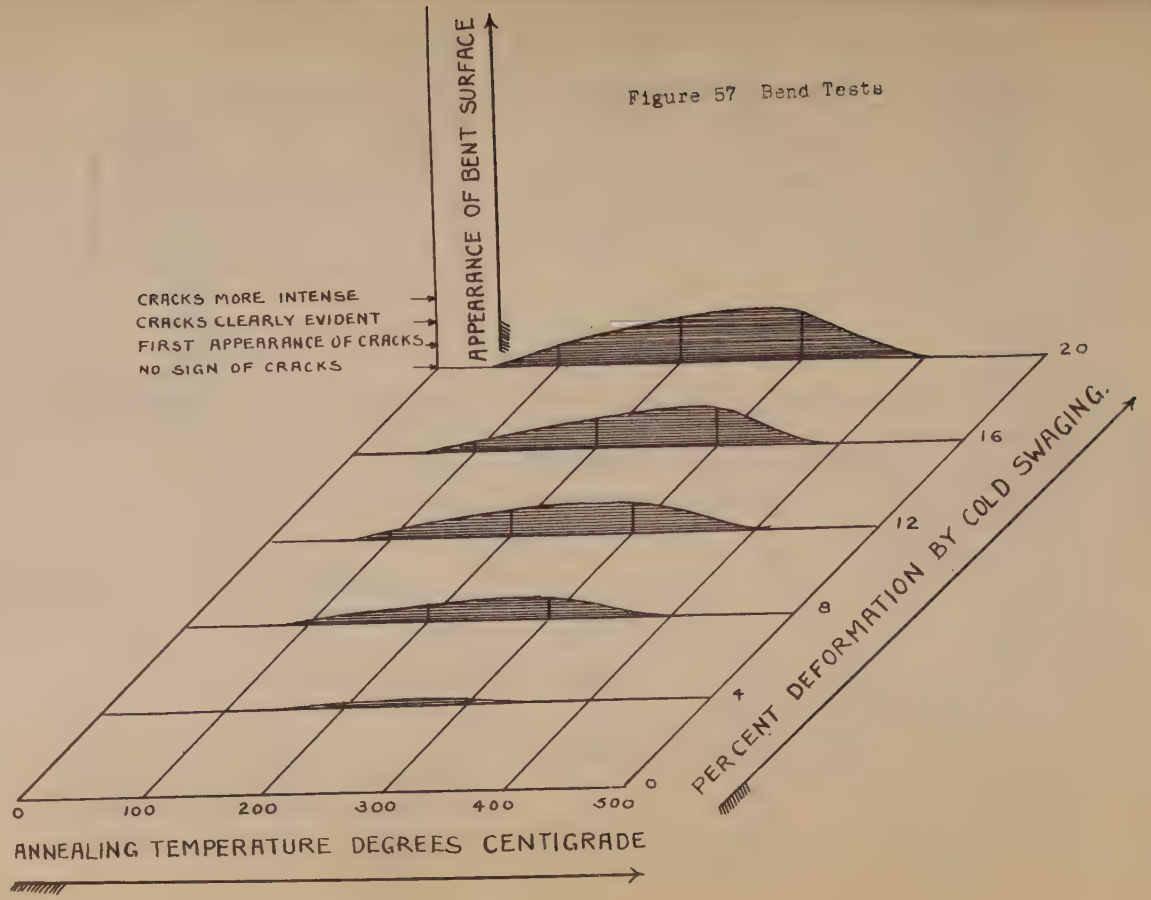


TABLE IV

BEND TESTS
(180° Angle of Bend around a 5/8" diameter mandrel)

Specimen Number	Percent Cold Worked	Annealing Treatment after Cold Working (1-hr)	Remarks
1		0	No sign of checks
2			" " " "
3		100	No sign of cracking
4			" " " "
5		200	" " " "
6			" " " "
7	4%	300	" " " "
8			" " " "
9		400	" " " "
10			" " " "
11		500	" " " "
12			" " " "
13		0	No signs of cracking
14			" " " "
15		100	" " " "
16			" " " "
17		200	Cracking commenced
18	8%		" "
19		300	Cracks evident
20			" "
21		400	No cracks
22			" "
23		500	" "
24			" "
25 & 26		0	No signs of cracks
27 & 28		100	" " " "
29 & 30	12%	200	Cracks Evident
31 & 32		300	" "
33 & 34		400	No cracks
35 & 36		500	" "
37 & 38		0	No cracks
39 & 40		100	" "
41 & 42		200	Cracks evident
43 & 44	16%	300	" "
45 & 46		400	No cracks
47 & 48		500	" "
49 & 50		0	No cracks
51 & 52		100	Signs of Cracks
53 & 54		200	Cracks evident
55 & 56	20%	300	" "
58 & 58		400	No cracks
59 & 60		500	" "

TABLE V

IMPACT RESISTANCE

Specimen No.	Percent Cold Work	Annealing Temp. 1 Hour Period	Energy Absorbed in Foot Lbs. & Average
1 2	4	Not Annealed	89 87 88
3 4	"	100° C.	83 87 85
5,6,7,8	"	200° C.	78,79,77 78
9,10,11,12	"	300° C.	73,79,80,80 78
13 14	"	400° C.	82.5 89 86
15 16	"	500° C.	87 87.2 87
17 18	8	Not Annealed	84 81 82.5
19,20,21,22	"	100° C.	69,75,71,73 72
23,24,25,26	"	200° C.	66,70,68,70 68.5
27 28	"	300° C	74 78 76
29 30	"	400° C.	76 76 76
31 32	"	500° C.	91 87 89
33 34	12	Not Annealed	79 81 80
35,36,37,38	"	100° C.	74,72,73 73
39 40	"	200° C.	68 70 69
41 42	"	300° C.	77 73 75
43 44	"	400° C.	75 75 75
45 46	"	500° C.	89 81 85
47 48	16	Not Annealed	80 79.5 80
49 50	"	100° C.	84 82 83
51 52	"	200° C.	71 69 70
53,54,55,56	"	300° C.	65,64,60,66 63.5
57,58,59,60	"	400° C.	88,89,91,81 87
61 62	"	500° C.	94 95 94.5
63 64	20	Not Annealed	79 77 78
65 66	"	100° C.	75 77 76
67 68	"	200° C.	59 63 61
69 70	"	300° C.	62 60 61
71 72	"	400° C.	75 78 76.5
73 74	"	500° C.	84 84

No impact values were recorded for numbers 5, 35 and 73 because flaws were found in the steel.

IMPACT TEST SPECIMEN

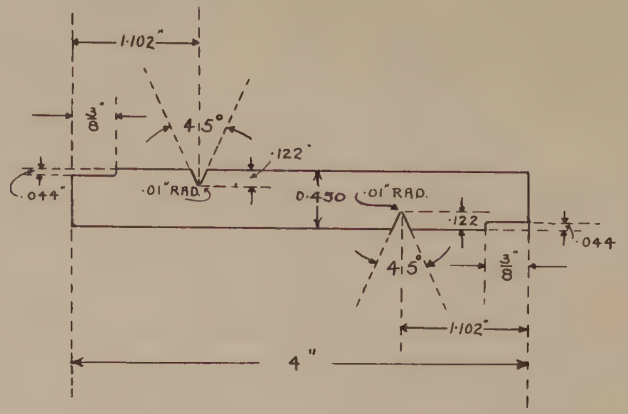


Figure 58

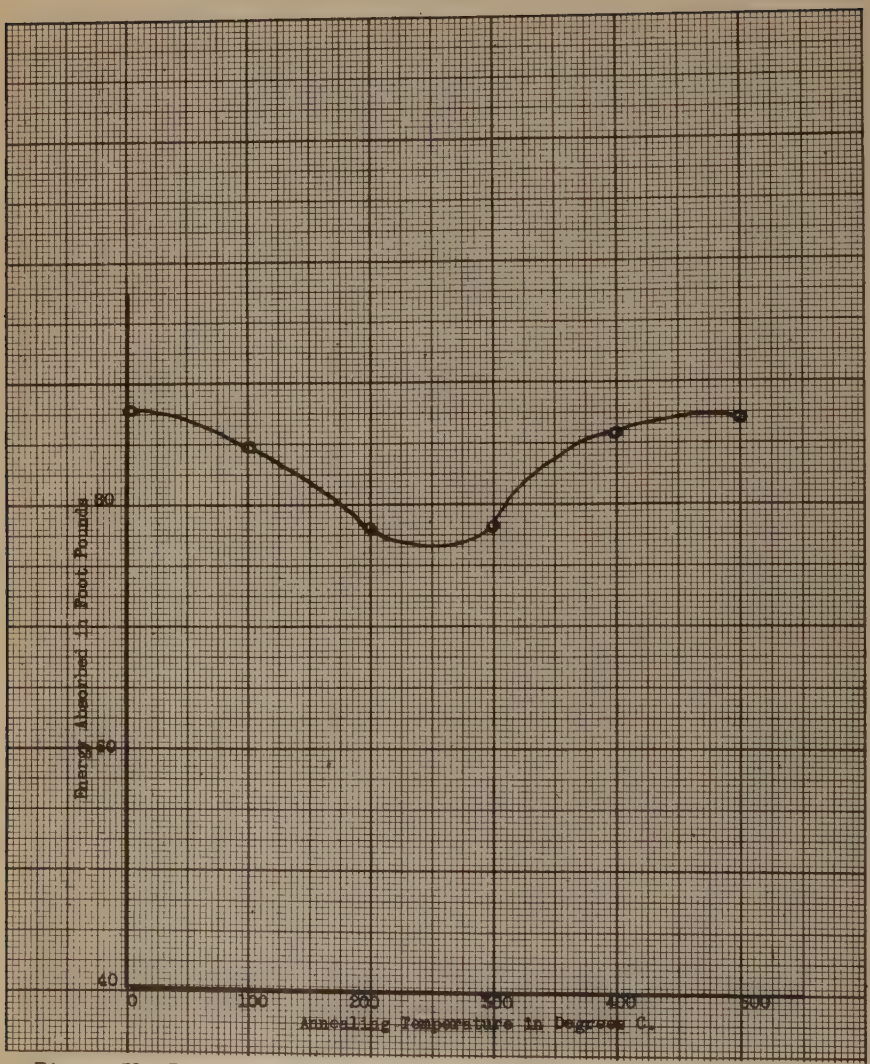


Figure 59 Izod Impact Values for 0.22% C. Steel Cold Worked 4% and Annealed.

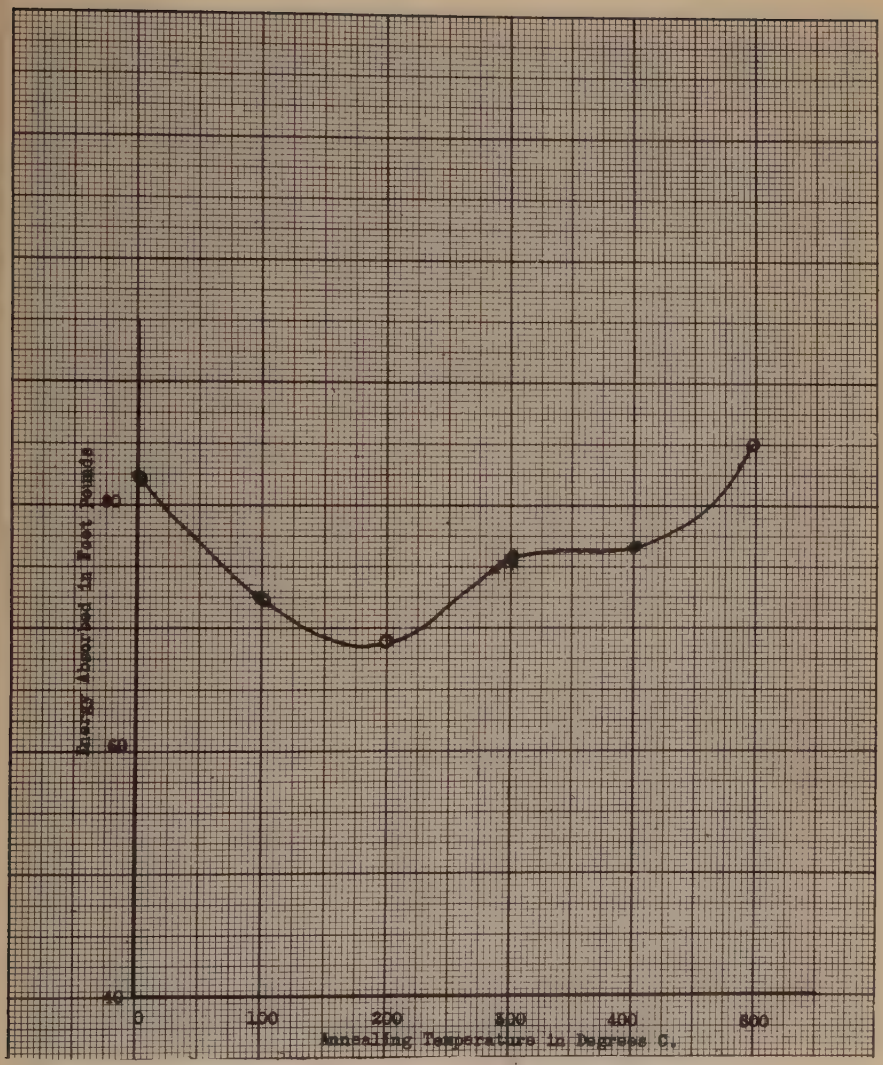


Figure 60 Izod Impact Values for 0.22% Carbon Steel Cold Worked 8% and Annealed.

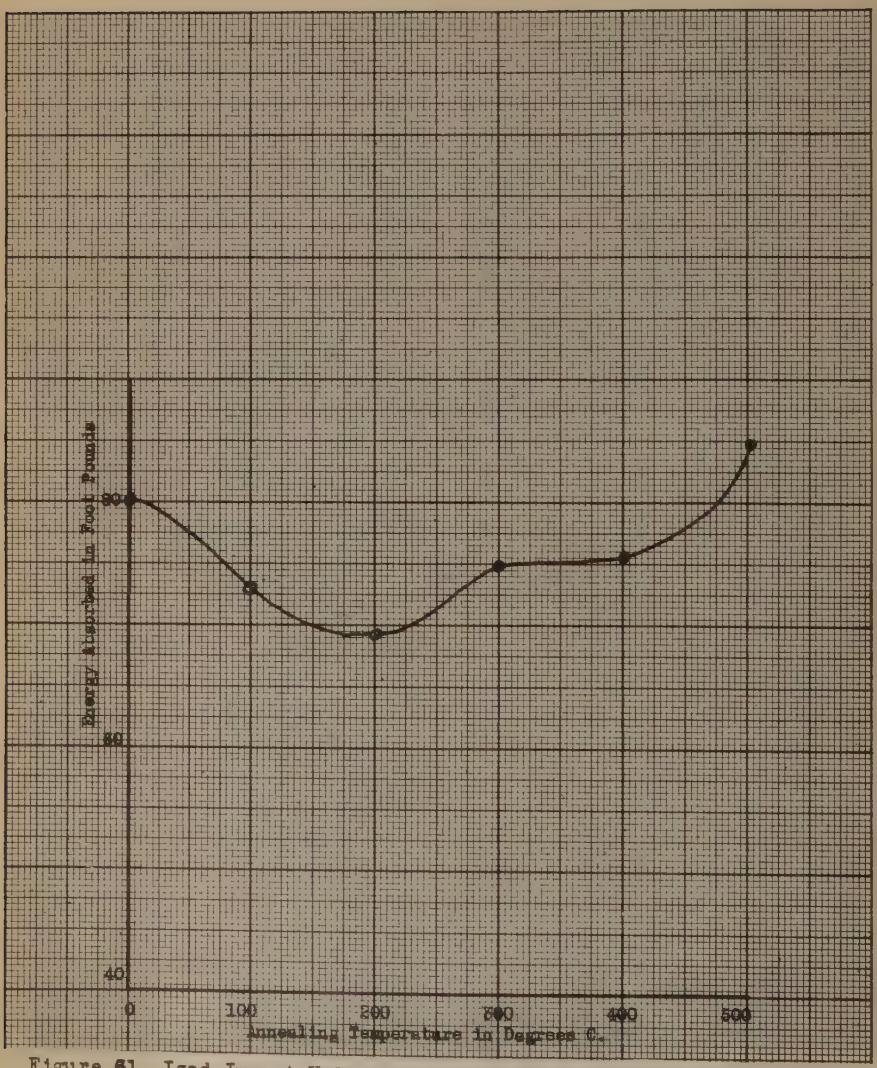


Figure 61 Izod Impact Values for 0.23% C. Steel Cold Worked 12% and Annealed.

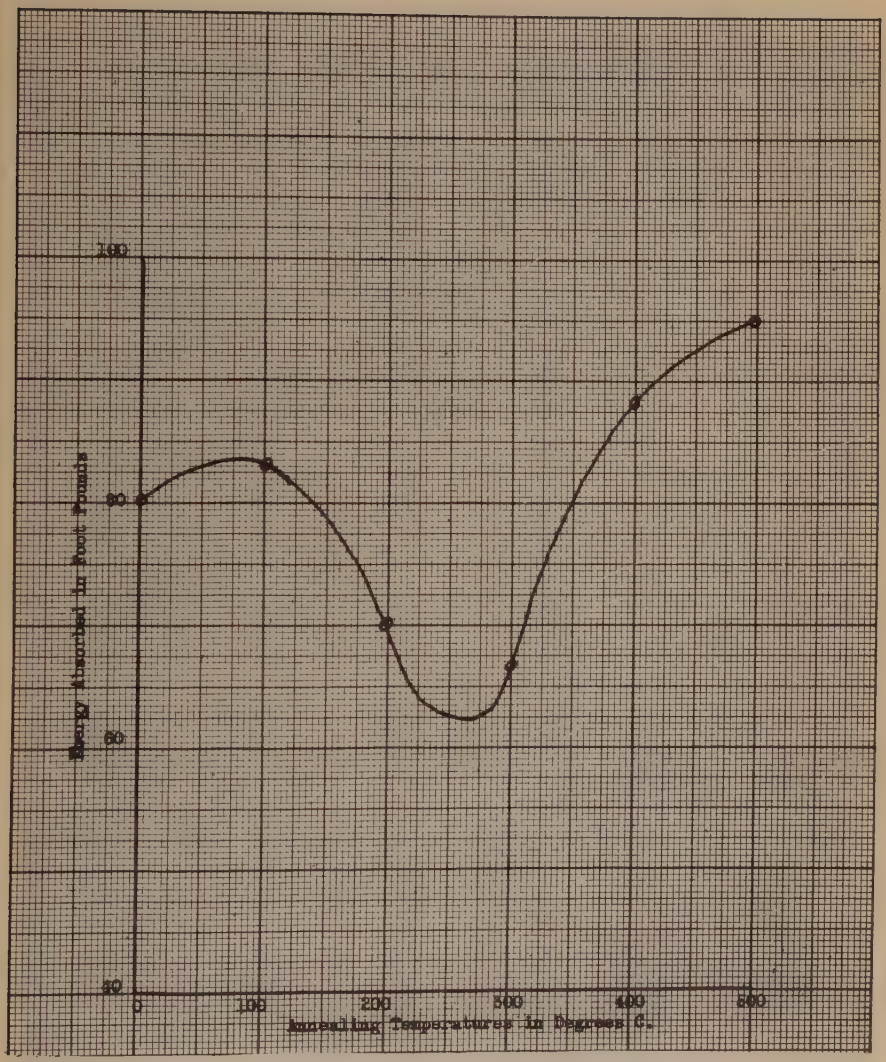


Figure 62. Izod Impact Values for 0.22% C. Steel Cold Worked 16% and Annealed.

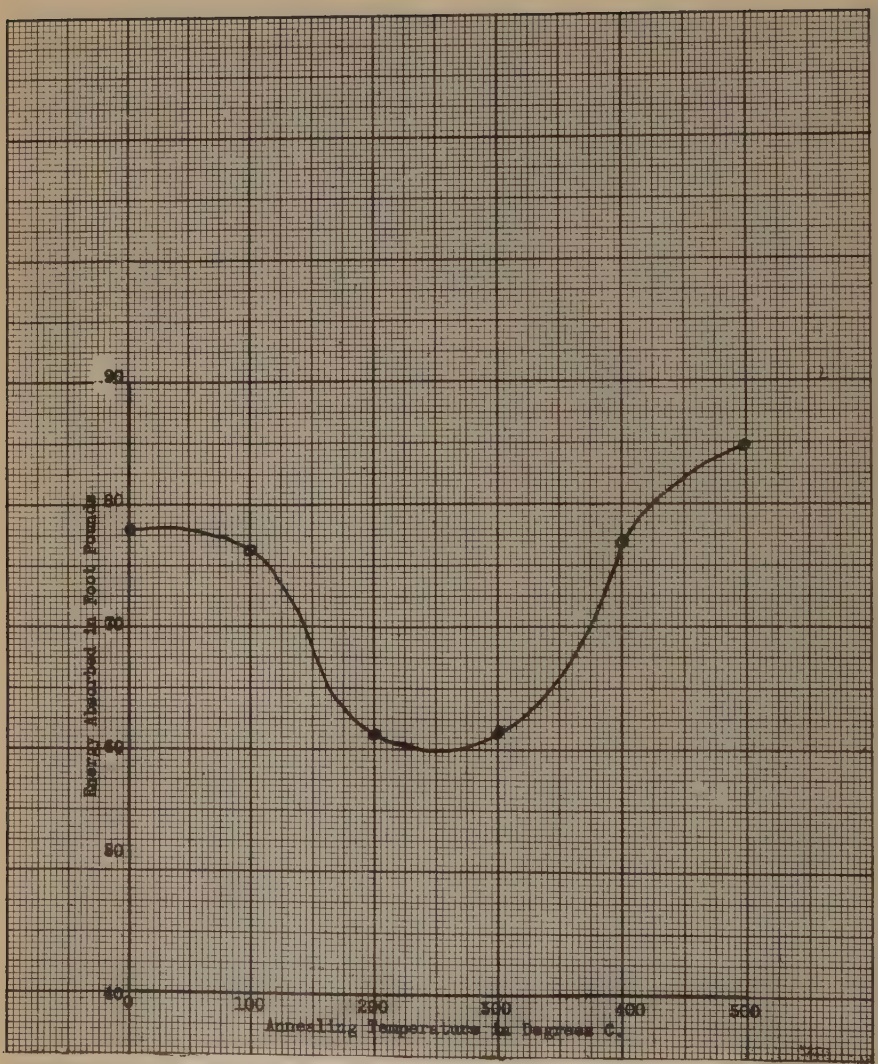


Figure 63 Izcd Impact Values for 0.22% C. Steel Cold Worked 20% and Annealed.

manganese content (0.89%). The lowest value of 61 foot-pounds obtained in these tests far exceeds the values usually common to mild steel which contains a much lower percentage of manganese (about .36%).

Korber and Dreyer[25], in 1921, as well as Bauer[2] in 1928, found that the notched toughness of cold worked mild steel was lowered whenever annealed at low temperatures. In no case did they get figures which approached an impact resistance of 61 foot-pounds; their minimum value more closely approached 10 foot-pounds. Mauer and Maitlander[26] found that 3.5% nickel steel cold worked from 5 to 20% has its impact resistance lowered from 40 to 75% on annealing at 300° C.

Only recently, May, 1929, we find Bolsover[39] giving results obtained while investigating steel cold worked by elongation 10%, followed by 30 minutes annealing at temperatures up to 300° C. He obtained a shock resistance (Figures 64 and 65) after annealing at 250° C. and his figures show a drop from 70 foot-pounds (the value for hot rolled steel as received) to 10 foot-pounds. This drop, approximately 85%, is much greater than was found in these tests. His original value of 70 foot-pounds is quite high and is undoubtedly due to the high manganese content (0.60%) which is greater than in 0.14% carbon steel.

The curves in Figures 59 and 60 clearly reveal the fact that steel cold worked from 4 to 8% has its impact resistance only slightly reduced (a reduction of approximately 14%) on annealing at low temperatures. On the other hand, steel cold worked 12 to 20% prior to annealing has its impact resistance further reduced (23%) on annealing in the critical range 150° to 300° C. (Figure 66).

Although previous investigators on the impact resistance of mild steel found that 300° C. was the critical annealing temperature for the lowest impact resistance, this investigation proved that for this steel 200 and 250° C. are the most critical temperatures.

Conclusions

1. This steel when cold worked has its impact resistance lowered if annealed within the temperature range of 150-300° C.
2. The reduction in notched bar impact resistance increases with the amount of cold work followed by annealing within the temperature range of 150-300° C.
3. The impact resistance of 0.22% carbon mild steel having

a manganese content of approximately 0.89% is much higher than that of the usual mild steel (0.18% carbon and 0.34% manganese) and is much less affected by low temperature annealing.

4. The minimum impact values for this cold worked steel are obtained after annealing at either 200 or 250° C.

PROPERTIES REVEALED BY THE TENSION TEST

The tension test today is accepted by engineers as furnishing satisfactory and fundamental indications of the quality of structural material. At times it is often supplemented by hardness tests such as the Brinell and Rockwell tests and in cases where shock absorbing information is desired, impact tests on notched specimens are widely used. The true value of the tension test has often been questioned. Some argue that since the material is subjected to simple tension, it is not a true criterion of the "strength" of the material in service, where it is subjected to a complicated system of forces. On the other hand it can be shown that the tension test does involve complicated stress distribution.

The tension test involves such terms as elastic limit, proportional limit, yield point, ultimate strength, elongation and reduction of area. The first four terms relate to the strength of the material, whereas the latter two—elongation and reduction of area—are measures of ductility. The value of elongation and reduction of area as measures of ductility is questioned by some observers who associate this property with plastic changes of length, such as in the tensile test and wire drawing.

Although most of the above terms are defined, their real significance is not fully understood. The question frequently arises, what is the true meaning of the yield point? It is known that when the yield stress is reached plastic flow results with the consequent appearance of permanent slip within the crystals. Because of the irregular orientation of the crystals, slip does not occur simultaneously in all crystals. In fact those crystals slip first which are unfavorably situated in regard to resisting the shear stress developed in tension. This feature, as well as the process of hardening which occurs in deformed crystals accounts for the fluctuation in stress due to yield and the higher loads at which the specimen breaks.

Noteworthy contributions concerning the yield point and its

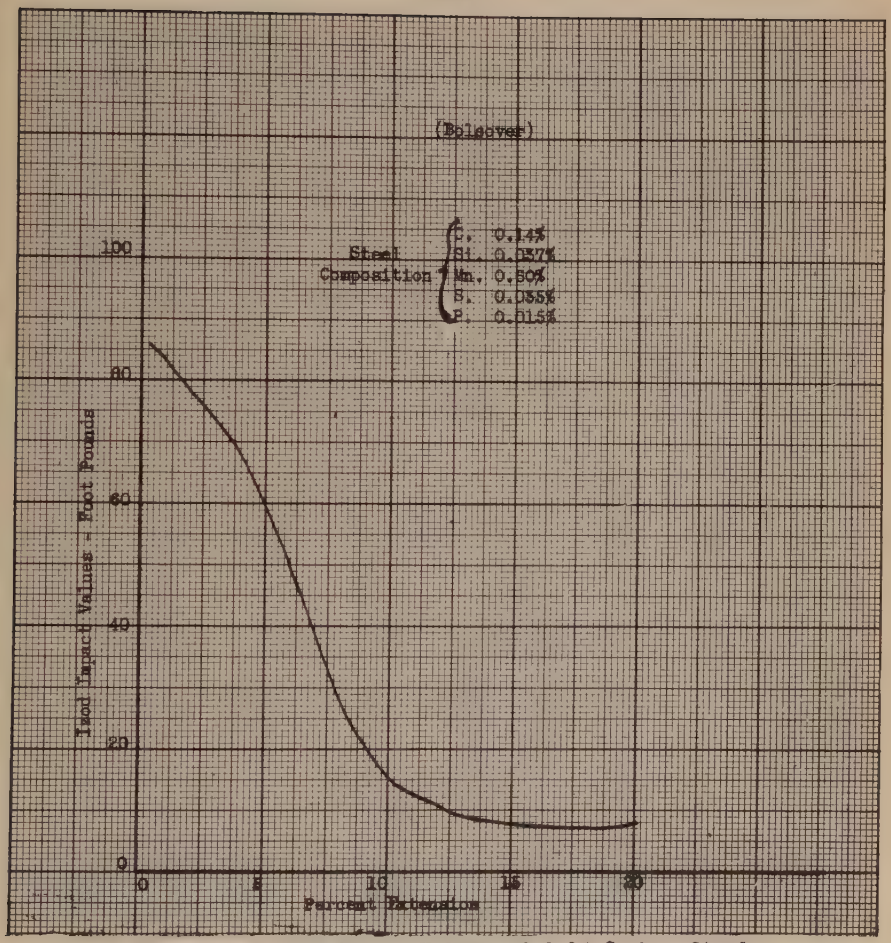


Figure 64 Izod Impact Values of 0.14 Carbon Steel Cold Worked by Extension Various Amounts Followed by a 30 Minute Anneal at 250° C.

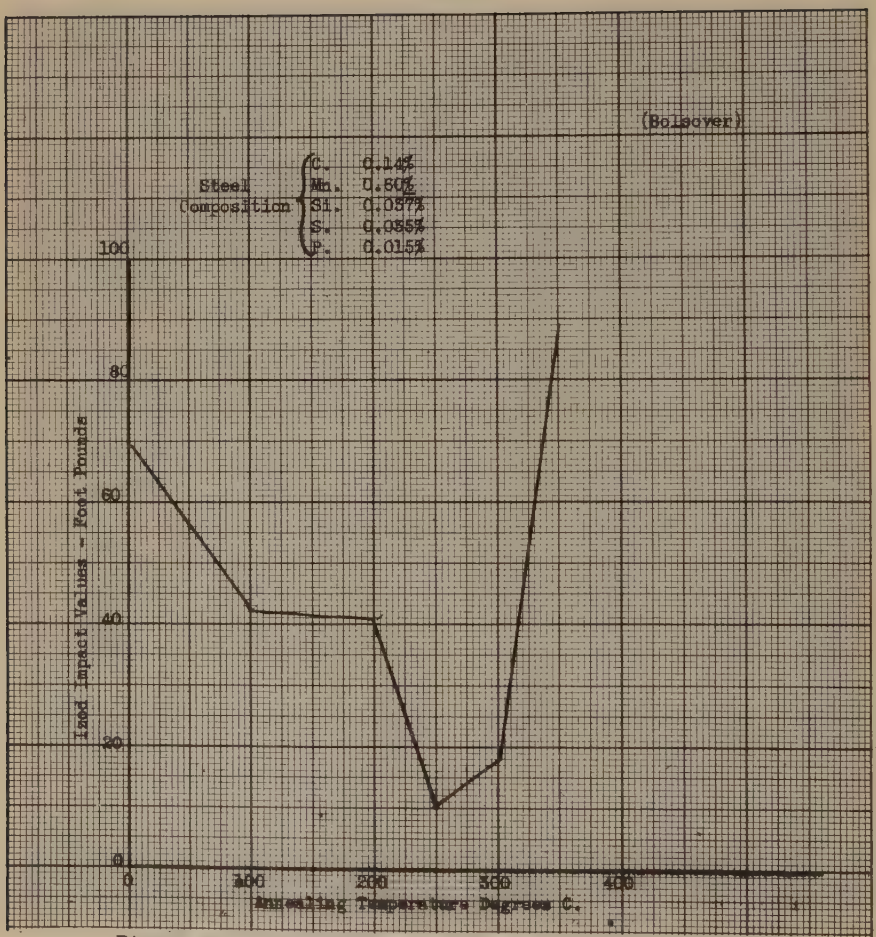


Figure 65 Izod Impact Values of Dead Soft Steel Cold Worked 10% by Elongation Followed by Annealing for Periods of 30 Minutes.

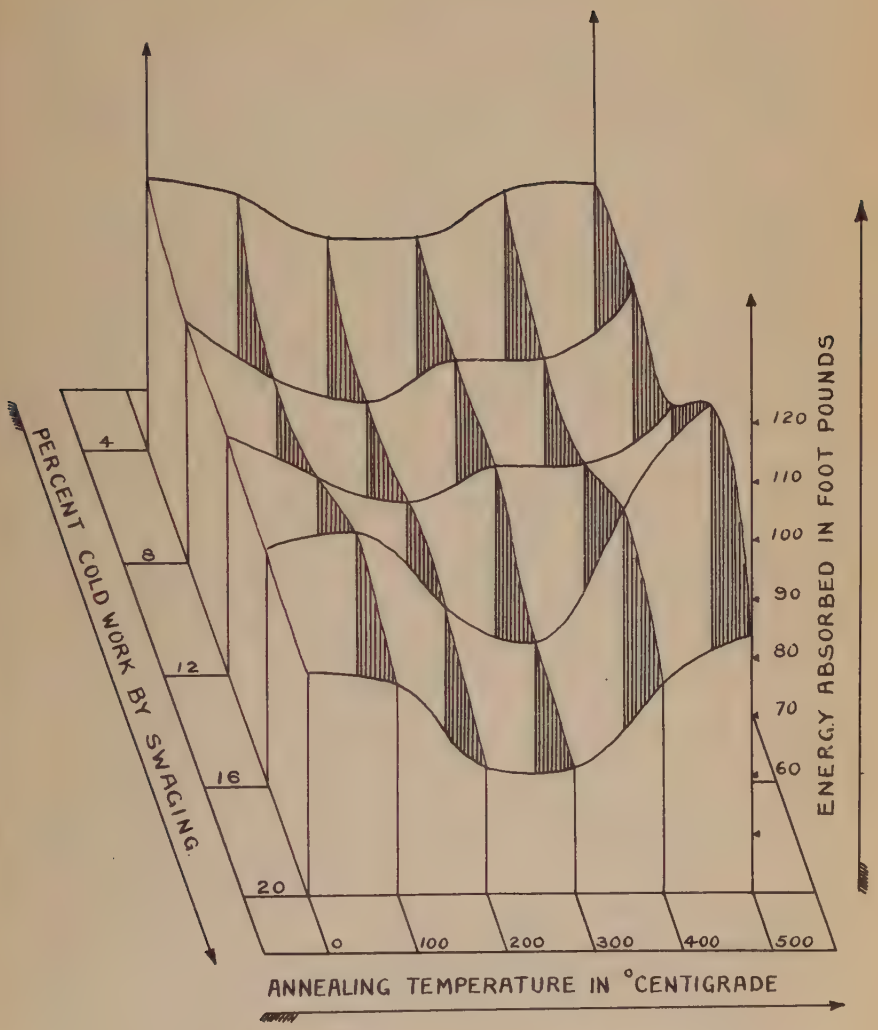


Figure 66 Composite Diagram Showing the Effect of Cold Working Various Amounts Followed by Low Temperature Annealing on the Izod Impact Values of 0.22% C. Steels.

significance have been made by Ludwik[77], Moses [75], Sachs [77], and Koster[73]—all German investigators. They discovered that the resistance of a material to stress alternation, so called fatigue, depends mostly upon its tensile strength (hardness and yield point) rather than upon the ease of working, such as elongation and reduction of area. These latter properties are not standards by the use of which failure from fatigue can be avoided. In fact, Dr. Ludwik[77] maintains the values of elongation, reduction of area, (and ultimate strength) are no trustworthy indication of the probable behavior of a metal under fatigue.

For brittle materials, the ultimate tensile strength is only an approximate measure of the cohesive strength of the substance. Since deformation (even if slight) has taken place prior to failure, it thus becomes no criterion of the unstrained metal, especially in regard to the intercrystalline cohesion. Therefore, it may be stated that whenever a substance possesses a low cohesive strength in comparison to the resistance to deformation, that material is brittle and when tested by impact will be accompanied by a low value.

In summarizing these considerations, it becomes apparent therefore that the relative magnitudes of the cohesion and internal friction or, in other words, of the ability to withstand tearing and resistance to shear, have a very important bearing on the brittleness of a material. In a normal ductile material, brittleness will immediately ensue if the relationship between these two properties is lessened even by a small amount from a certain limiting value.

At this point two questions arise:

1. Can the tensile test reveal this relationship?
2. Can it be measured and illustrated?

Evidence Advanced Proving that Tensile Tests Reveal Brittleness .....in a Normally Tough Material

In considering the results obtained in the present investigation, it was discovered that the yield point could be altered, raised or lowered, depending on the condition of the material prior to any annealing treatment. This yield point, moreover, appears to have a definite relationship to the ultimate strength of the material.

A distinctive method of disclosing this relationship is clearly shown in Figures 67-72. The difference between the ultimate strength and the yield point, due to various degrees of cold work

prior to annealing at different temperatures has been plotted. Figure 40 gives the tensile strength and the yield point for 0.22% carbon steel, cold worked 4% followed by annealing at from 0 to 600° C. It shows that the relative cohesive strength and shearing strength are gradually approaching a certain limiting value. In fact, it is accepted that when the resistance of a material to shear becomes as great as its resistance in tension that substance exhibits brittleness, otherwise a considerable degree of deformation or change of shape would follow under the acting stresses long before rupture occurs. Therefore, a reasonably low shearing strength in comparison to cohesive strength is a measure of ductility.

Now, then, how will the tension tests show this feature? A close study of both the yield point and ultimate strength is necessary. A yield point indicates ability of crystals to slip without rupture while the ultimate strength indicates cohesiveness. When the yield point approaches the ultimate strength, even by a small amount, signs of brittleness in that material may be expected. Furthermore, if the yield point practically disappears, then a condition for brittleness has been satisfied.

Figure 68 shows that this steel loses a considerable amount of toughness when cold worked from 10 to 20% and annealed at 100 to 200° C. Indeed it has developed a considerable amount of brittleness. A study of the other curves shows somewhat similar features.

Just recently, Bolsover[39] discovered that mild steel (0.14% carbon) becomes brittle as measured by the impact test, when cold worked by elongation 10 to 15% and annealed at 250° C., for thirty minutes. In his work Bolsover has made some tensile tests, the results of which have been utilized to form the sketch in Figure 73. Here it is immediately apparent that the difference between the ultimate strength and the yield point becomes less and less with the increase in the brittleness of this steel. This is a further verification of the feature brought out in the present investigation.

Finally, employing the method shown in Figure 74 it is discovered that whenever 0.22% carbon steel is cold worked from 10 to 20% prior to annealing at from 150 to 250° C., brittleness is imparted. This area is labeled "Area of Brittleness" in Figure 74.

Discussion

Any laws or rules which may be enunciated predicting when a normally tough material becomes brittle are of great importance. In order to draw conclusions it is necessary to compile the funda-

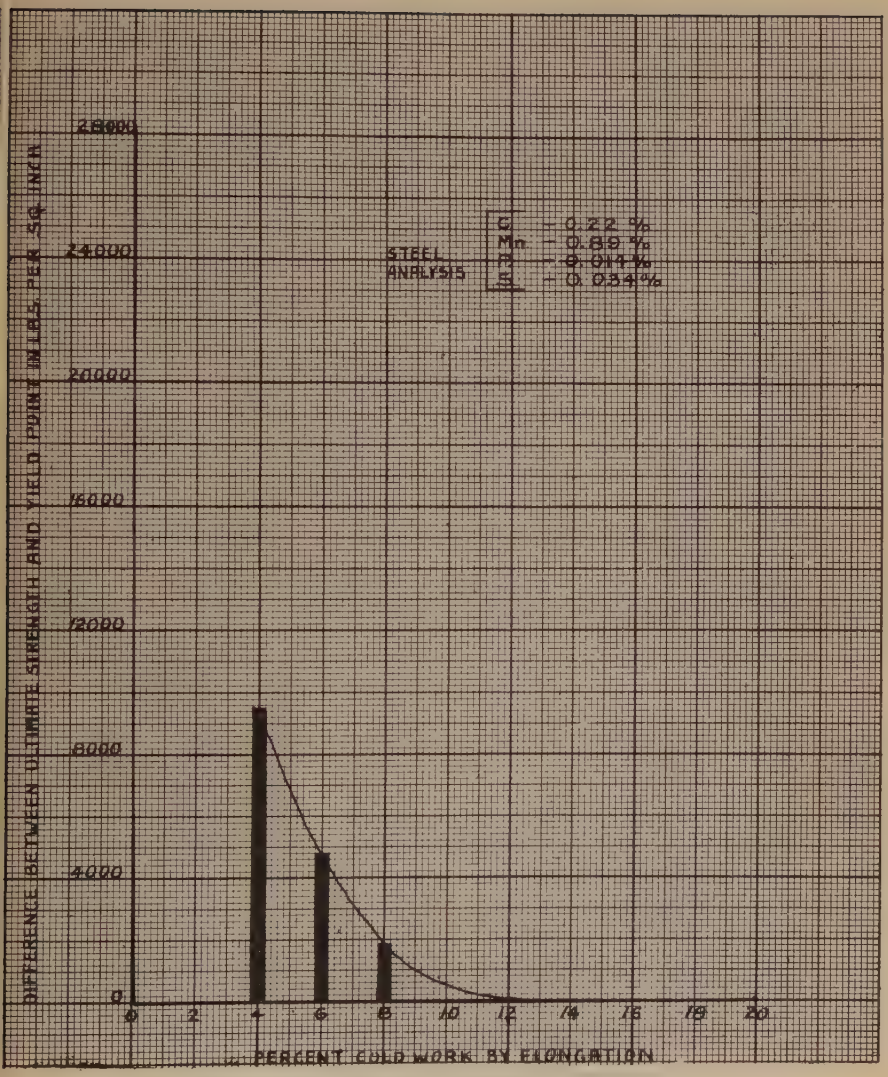


Figure 67 Difference Between Ultimate Strength and Yield Point Due to Various Degrees of Cold Work Followed by Annealing at 100° C.

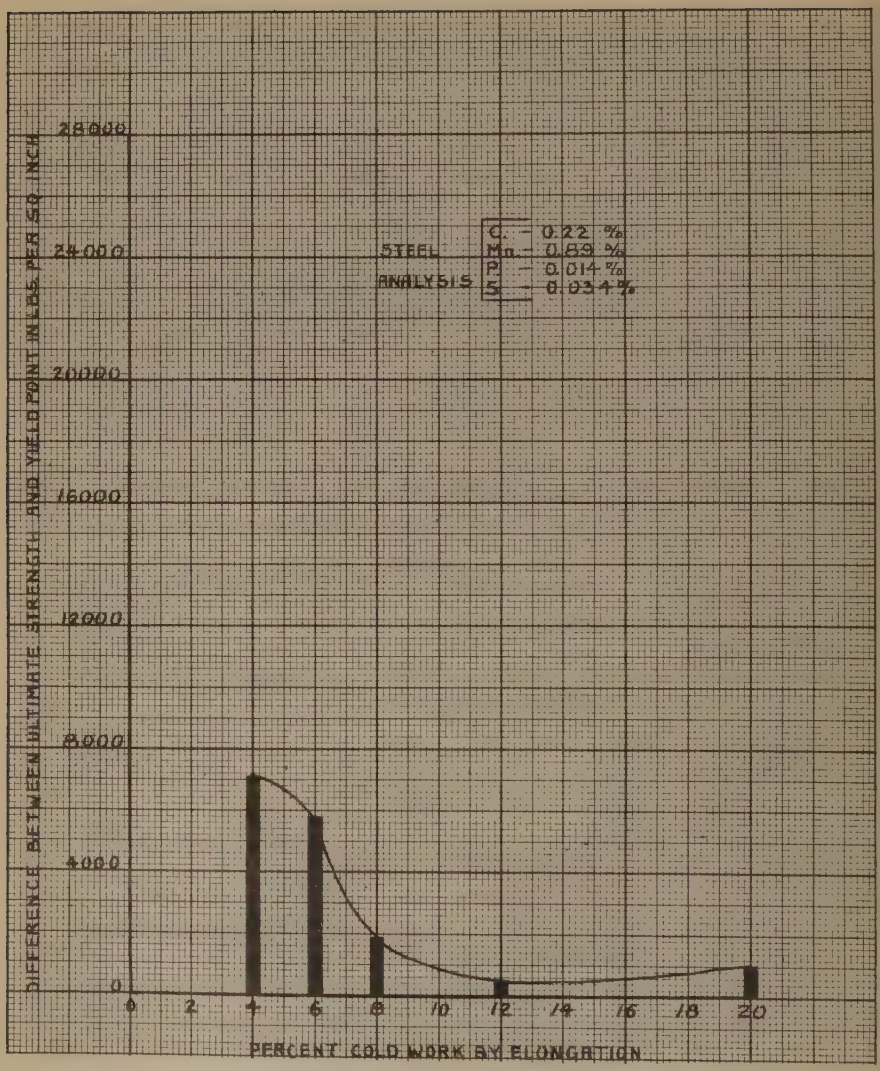


Figure 68 Difference Between Ultimate Strength and Yield Point Due to Various Degrees of Cold Work Follwed by Annealing at 200° C.

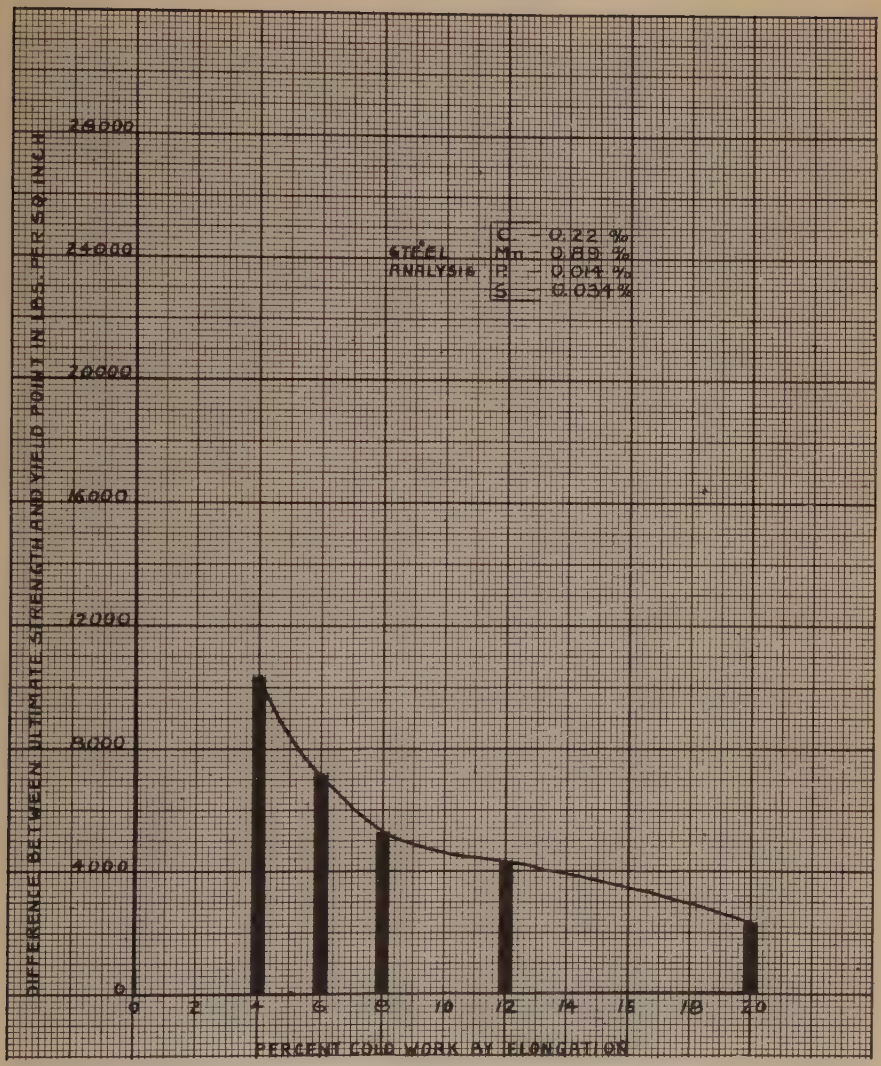


Figure 69 Difference Between Ultimate Strength and Yield Point Due to Various Degrees of Cold Work Followed by Annealing at 300° C.

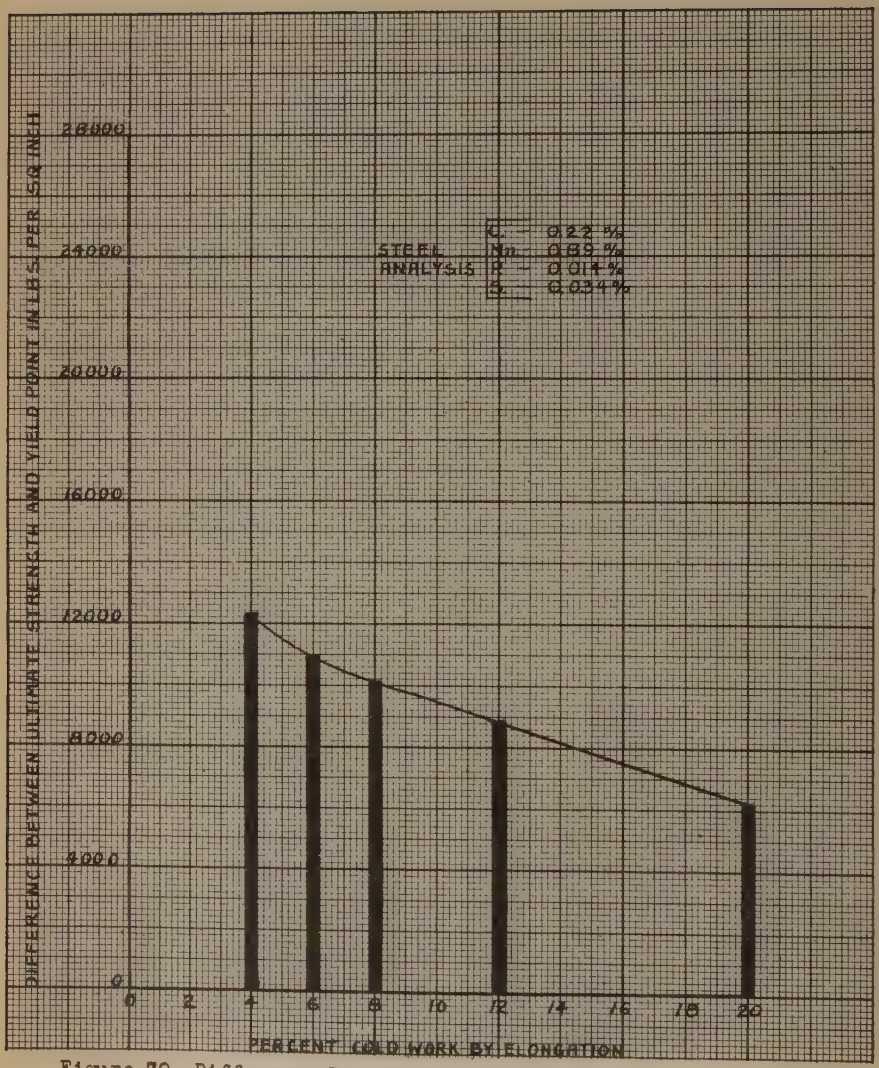


Figure 70 Difference Between Ultimate Strength and Yield Point Due to Various Degrees of Cold Work Followed by Annealing at 400° C.

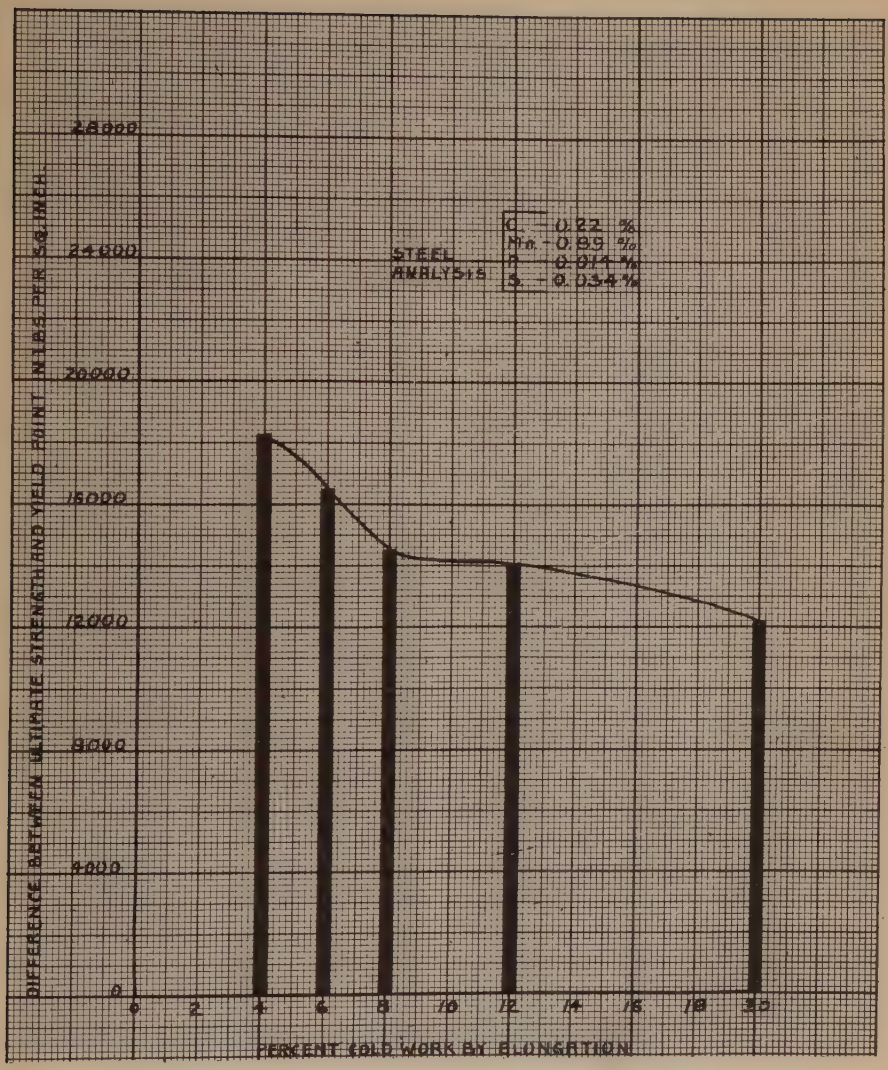


Figure 71 Difference Between Ultimate Strength and Yield Point Due to Various Degrees of Cold Work Followed by Annealing at 500° C.

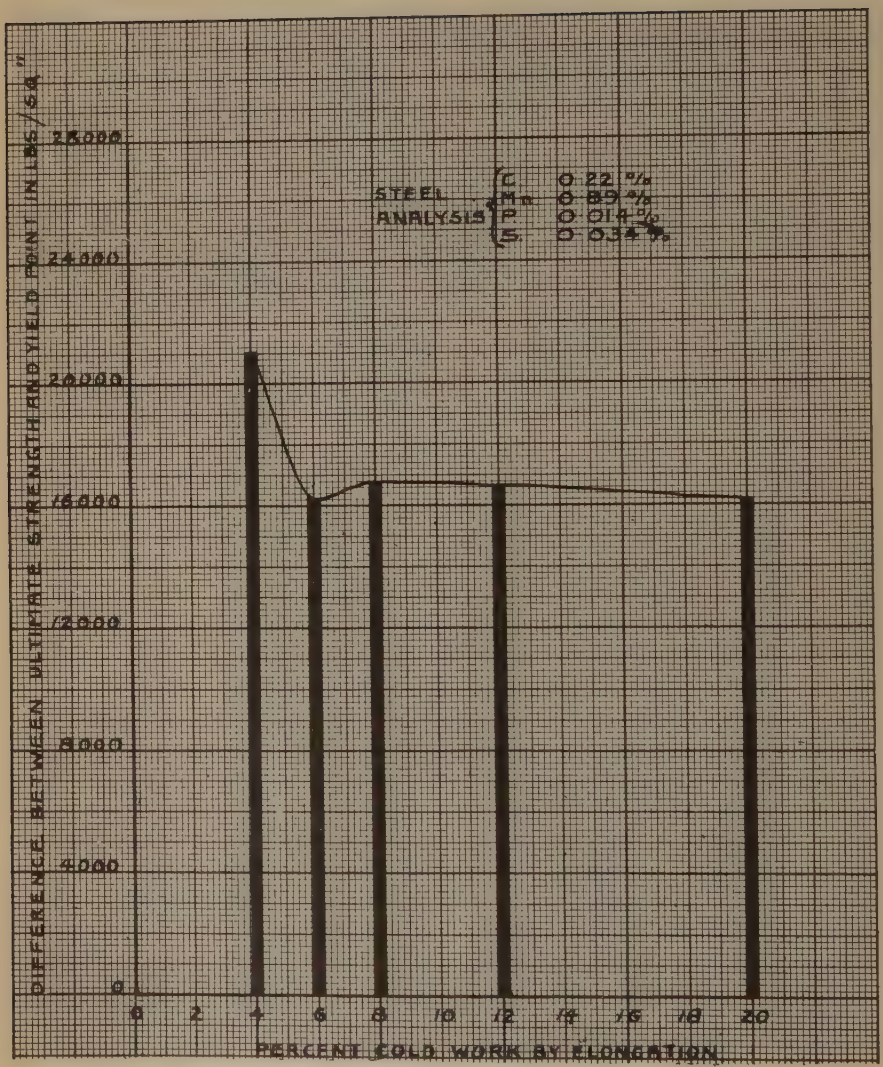
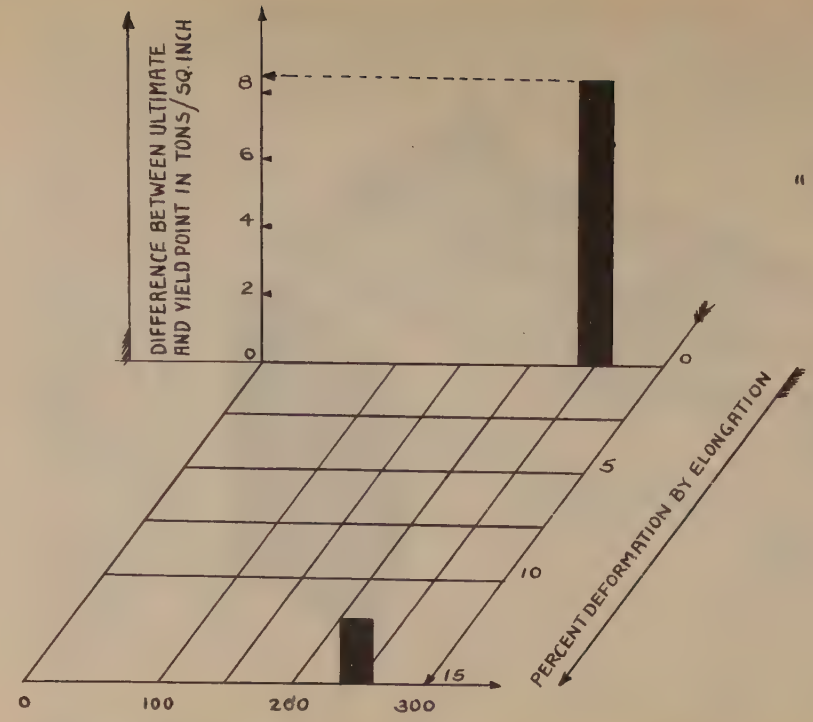


Figure 72 Difference between Ultimate Strength and Yield Point Due to Various Degrees of Cold Work Followed by Annealing at 600° C.



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"BOLSOVER" FIGURES
1929

Figure 73 Relationship Between Ultimate Strength and Yield Point as Affected by Cold Work, Prior to Low Temperature Annealing, for Periods of Thirty Minutes.

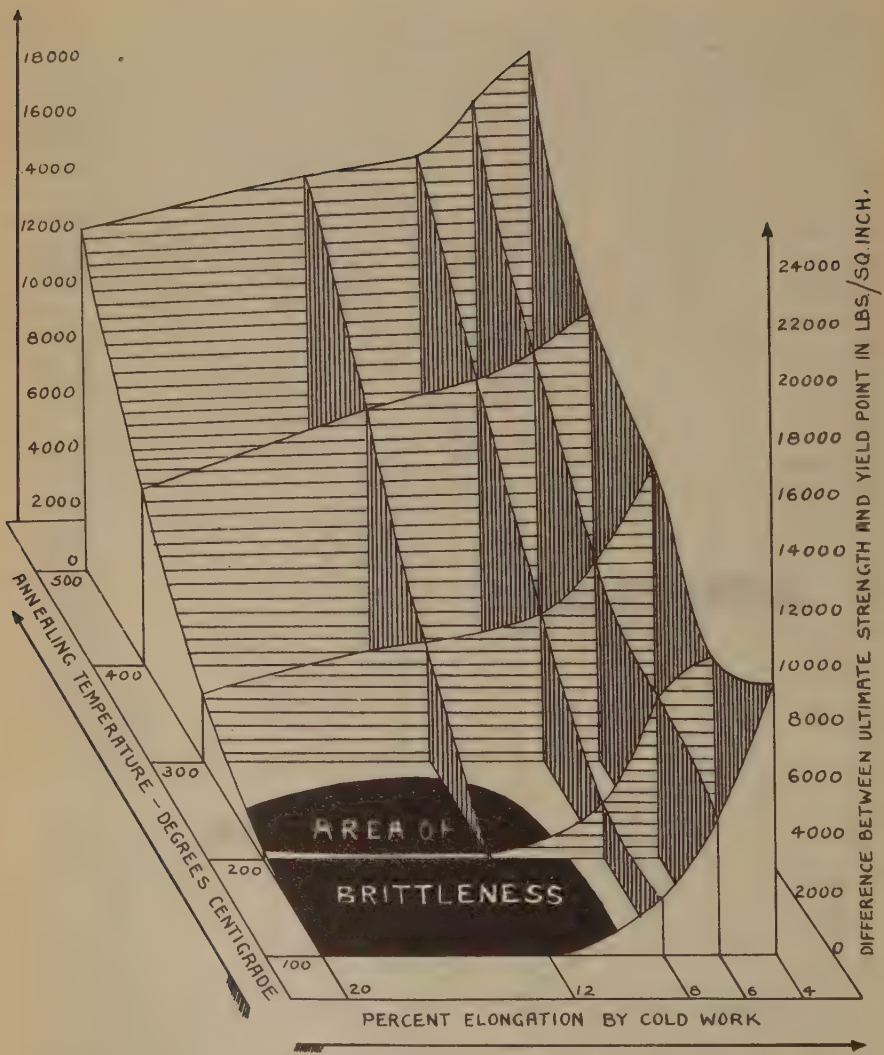

Figure 74 DIFFERENCES BETWEEN THE ULTIMATE STRENGTH AND YIELD POINT DUE TO VARIOUS DEGREES OF COLD WORK, AND FOLLOWED BY ANNEALING AT DIFFERENT TEMPERATURES.

mental properties of such substances. In this respect, the only substances which normally exhibit a yield point are:

1. Pure iron.
2. Steel.
3. Some aluminum zinc alloys.
4. Substances possessing the body centered cubic lattice.
5. Substances possessing eutectoid structure.
6. Substances possessing plasticity.
7. Substances possessing the property of elastic recovery.
8. Substances possessing the property of aging.

A careful study of this list shows that certain physical properties are dependent on certain conditions. For instance, elastic recovery after overstrain and plasticity are accepted as being common to the body centered cubic lattice. The peculiar phenomenon, aging, is a property of super-saturated solid solution. Furthermore, a eutectoid structure, as far as evidence points, is also a requirement for a yield point.

To recapitulate, it is found that the yield point is a characteristic possessed by materials having either one or both of the following properties:

1. Body centered cubic space lattice.
2. Eutectoid structure.

By deduction, it now becomes apparent that whenever the yield point disappears in a material, either one or both of the above necessary requirments for a yield point are altered. In fact, evidence appears to substantiate this fact. It was observed that when mild steel revealed no sharply defined yield point, the microstructure contained no cementite, or only thin broken veins of this substance[73]. Furthermore, this steel became brittle.

It is impossible with the evidence available to draw any general conclusions specifying when a material which is normally tough will become brittle, based on the above mentioned properties. The evidence available is too meager to draw any general conclusion Specifically, however, it can be stated:

1. Whenever a normally tough substance exhibiting a yield point is so treated that it disappears or that the relationship between the ultimate strength and the yield point is lowered from a certain limiting value, embrittling properties

are imparted. A convenient way of illustrating this is by using the diagram already employed. (Figure 74.)

2. The tension test reveals brittleness in a normally tough material by the relation of the yield point to ultimate strength.
3. In a normally tough material exhibiting a yield point, the moment the relationship between the yield point and ultimate strength is lessened from a certain limiting value, even to a slight extent, brittleness is imparted.

APPLICATION OF CONCLUSIONS TO AN INDUSTRIAL PROBLEM

The specific conclusions obtained in this present investigation answers many questions involving the failure of material in the industrial field. A few failures of this nature have been recounted. The importance attached to the factors involved in shaping structural brackets from large I-Beams with an oxyacetylene torch, made it necessary, first, to determine the degree and location of plastic deformation imparted; and second, to determine the heat distribution in the bracket during the shaping process. With such information available, recourse to the specific conclusions of this research would account for these failures.

The degree and location of the plastic strains imparted under some of the conditions encountered in the industry have been determined by Krefeld[79]. A determination of the heat distribution in a structural detail as well as an analysis of the material, however, will be the subject of this section of this work.

Descriptive

A 6 foot x 24 inch I-Beam (Figure 75) such as is used in the structural field was employed. Its carbon content was 0.24% and its microstructure was a mixture of ferrite and pearlite common to hot rolled mild steel.

Arrangement of Thermocouples

The temperatures were recorded with thermocouples at various parts of the I-beam during the cutting operation with an oxyacetylene torch. The arrangement of the thermocouples employed for this purpose is shown in Figure 76a. Figure 76b illustrates the method used for securing good contact between metal and couple.

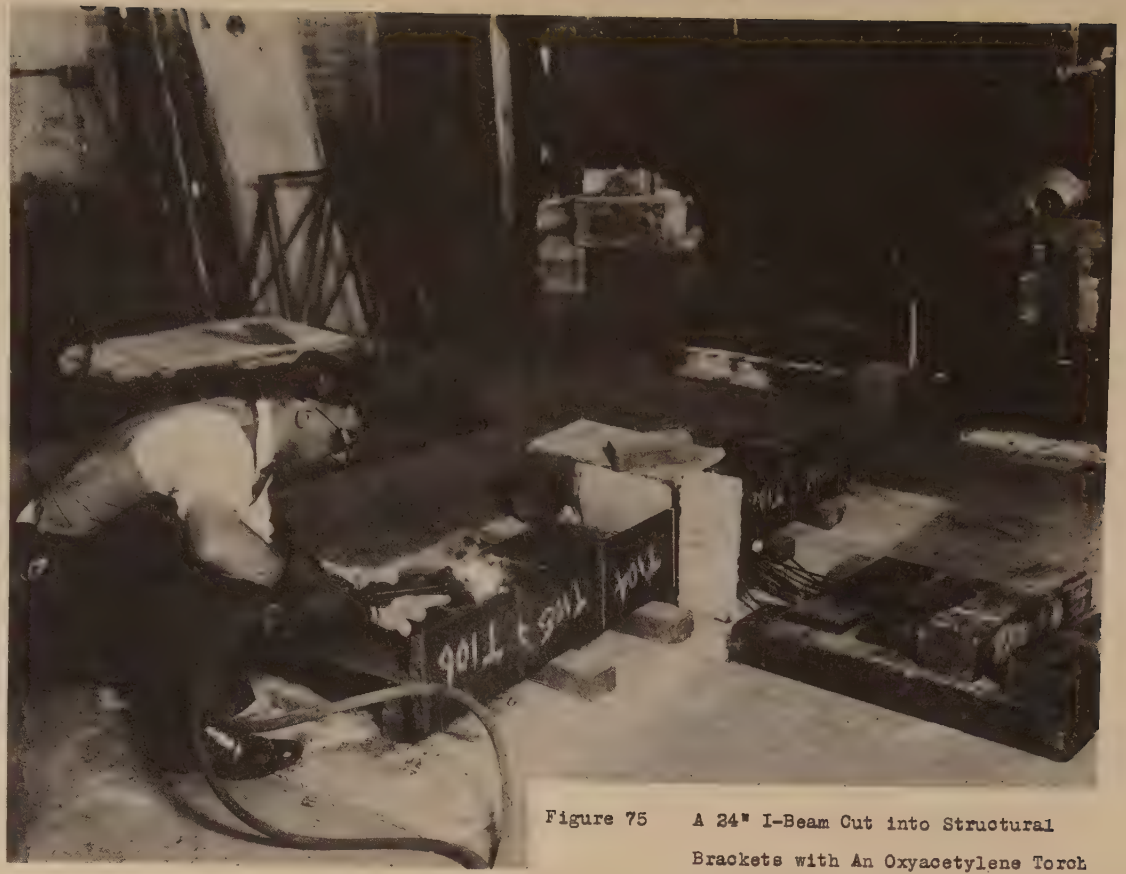

Figure 75 A 24" I-Beam Cut into Structural Brackets with An Oxyacetylene Torch

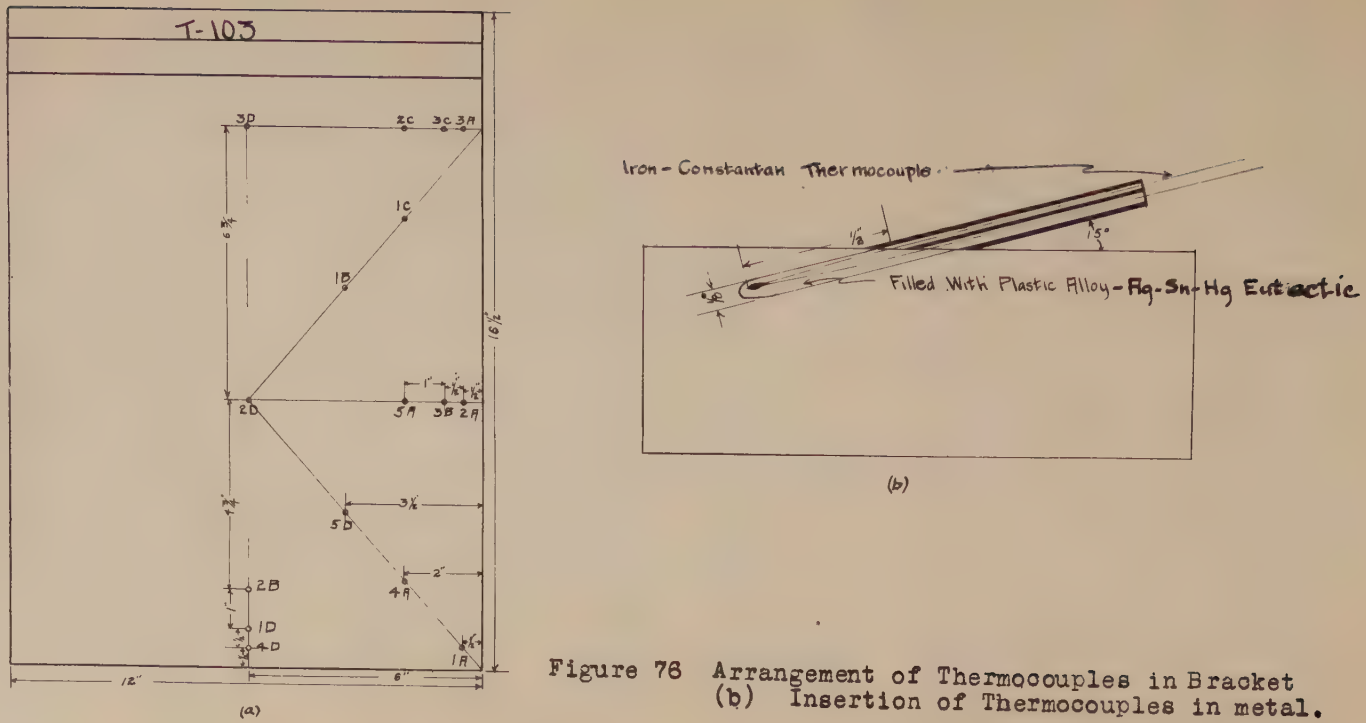

Figure 76 Arrangement of Thermocouples in Bracket
(b) Insertion of Thermocouples in metal.

The thermocouple tips were immersed in a tin-silver-mercury eutectic alloy; furthermore they were also protected by asbestos coverings.

Calibration of Thermocouples

These thermocouples, which were of iron and constantan wire, were connected to four pyrometers; five thermocouples to each of two Siemens and Halske, and three to each of two Keiser and Halske galvanometers. After the pyrometers and connections were carefully examined, the couples were checked against a standard thermocouple as well as against a calibrated thermometer which read to 350° C.

Preliminary experiments on small sections of I-beams determined the various sources of error involved in recording accurate temperatures during the oxyacetylene cutting operations. Such sources of error were carefully considered and eliminated as far as practical. In this way very accurate temperature measurements were made. The curves in Figures 77 and 78 are the results of over one thousand temperature readings.

Results

1. The curves in Figures 77 and 78 reveal that the highest temperatures were recorded nearest the edges and, furthermore, the temperature-time gradient was very steep at these sections. These maximum temperatures recorded were from 265-270° C. (510-519° F).
2. The structural brackets were also found to be subjected to very unequal heating by an oxyacetylene cutting operation. Moreover, the average temperatures to which these structural brackets were heated were approximately 105° C.-125° C. (225-250° F.) (Figures 77 and 78.)
3. Brackets which were punched as well as those not punched revealed plastic strains when they were etched with Fry's macroscopic reagent.
4. Areas plastically deformed by an operation prior to oxyacetylene cutting were heated to temperatures ranging from room to 270° C. (68-519°F.).

Discussion of Results

Heyn in his book "Physical Metallography"* discusses with his usual clearness the subject of strains in steels caused by unequal heating. In fact, he relates that whenever steel members are heated

unevenly, plastic deformation subsequently results to neutralize the strains set up if the elastic limit of the material is surpassed.

As a matter of fact Fry's macroetch process proved conclusively the existence of plastic deformation (Figure 79) and further that the elastic limit of the material had been exceeded in various parts. The experiments performed proved that whenever an I-beam is flame cut into structural brackets uneven heating occurs. (Figure 80.)

Since plastic deformation has been imparted by heat stress, the material really had undergone a double operation; first the material was plastically deformed, and second it received an annealing treatment below the critical range. In the case of structural brackets, the maximum annealing temperature was 270° C.

The specific conclusions of the first part of this investigation showed that tough steel has its toughness considerably reduced if such steels are cold worked followed by annealing at low temperatures. The critical annealing ranges found here were from 150° to 300° C. these temperatures applied to steel cold worked from 10 to 20%.

A Study of the Material

A microscopic study of these brackets failed to show any defects in the material. Plastic deformations were revealed by Fry's macroscopic etching process. These areas were examined microscopically but, as was the case with some former investigators, no essential difference between the dark and light sections could be detected. Figures 81-84 show views of a section of a bracket including the strain lines. It is apparent here that these lines are deep-seated.

Fry, who first discovered these strain lines, believes that they are the cause of "blue brittleness." This explanation can hardly be detected. Figures 81-84 show views of a section of a bracket 500° C. In this range of temperature "blue brittleness" in low carbon steel is removed.

In conclusion it may be stated that:

1. Structural brackets are unevenly strained in their manufacture, causing plastic deformation. (Figures 81, 82.)
2. Areas of plastic deformation in structural brackets were subjected to annealing at low temperatures—0-265° C. (Figure 80).

*pp. 275-291.

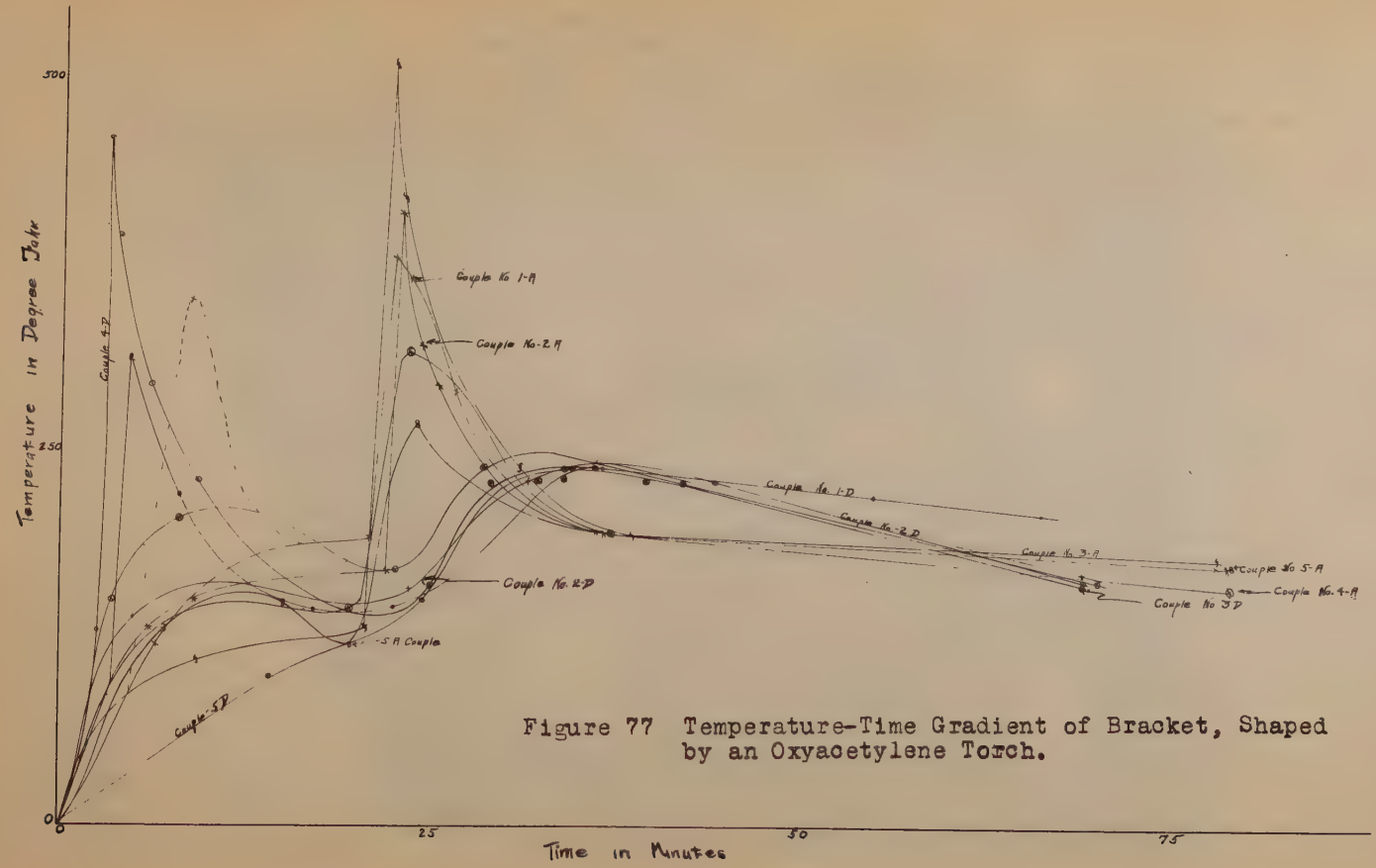

Figure 77 Temperature-Time Gradient of Bracket, Shaped by an Oxyacetylene Torch.

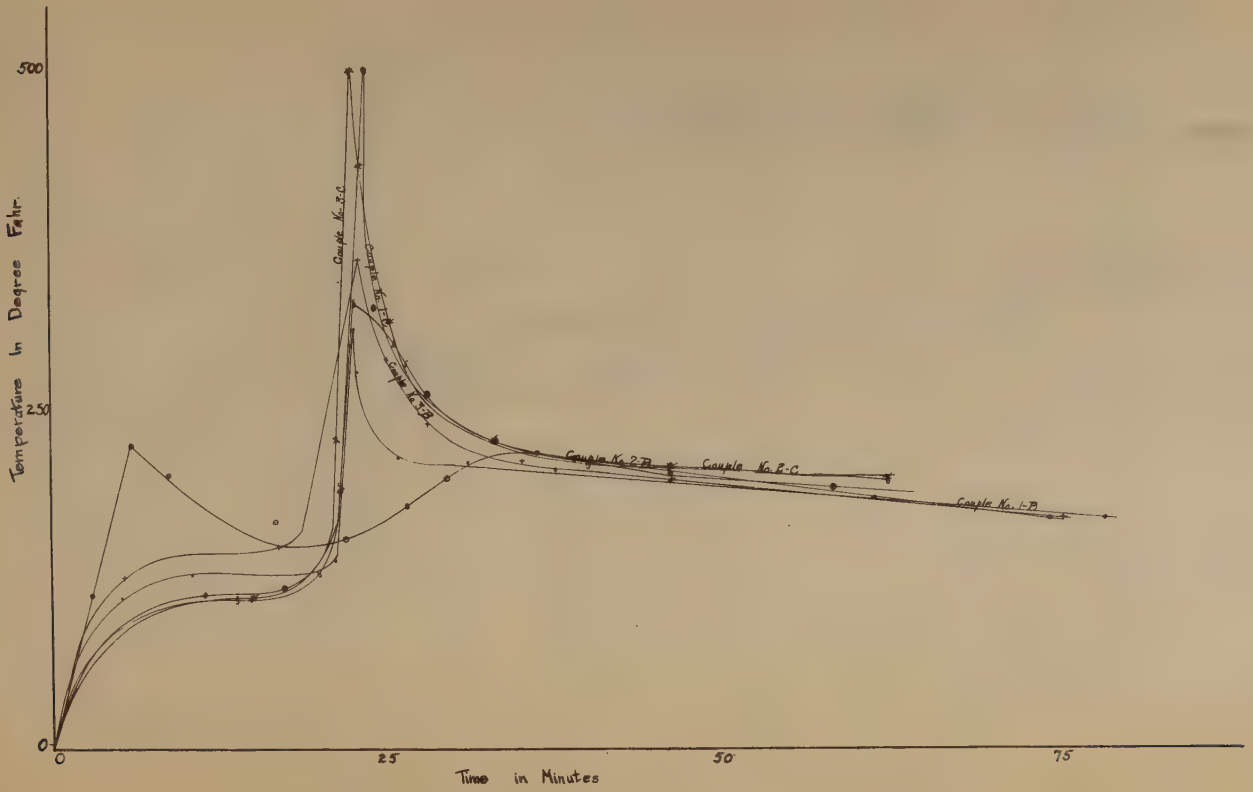

Figure 78 Temperature-Time Gradient of Bracket, Shaped by an Oxyacetylene Torch.

Figure 79 Plastic Areas in a Broken Bracket Etched with Fry's Reagent (Bracket Shaped by an Oxyacetylene Torch)

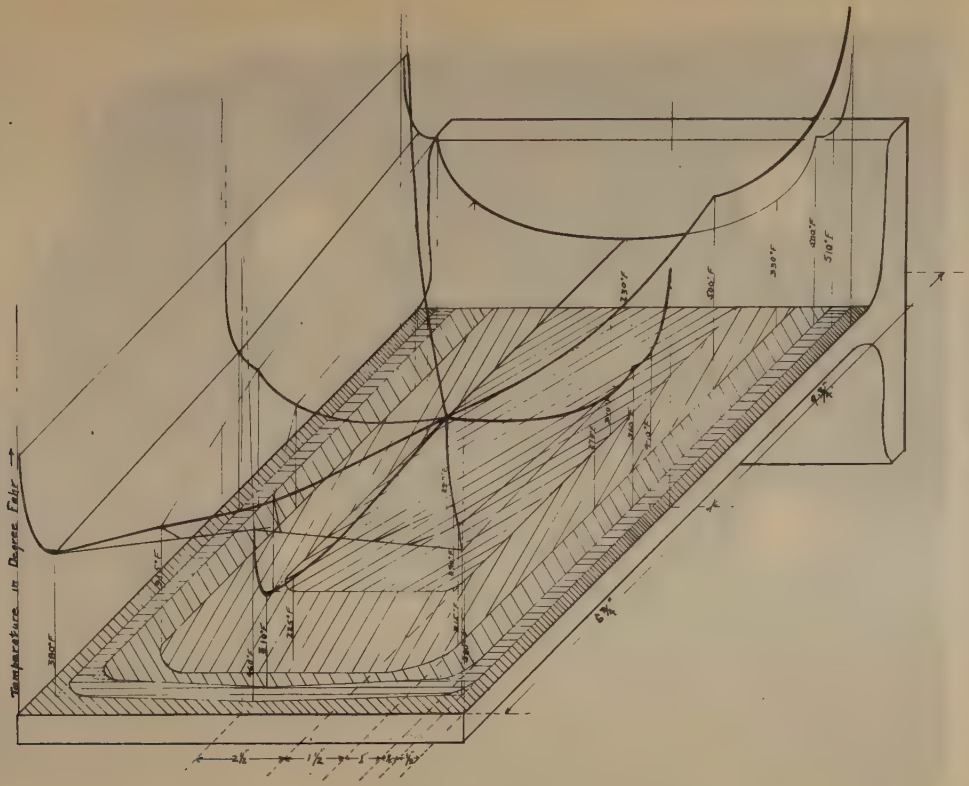

Figure 80 Heat Distribution in Brackets, Shaped by an Oxyacetylene Torch.

Figure 81 Plastic Strains Caused by Uneven Heating (Oxyacetylene Cutting)

Figure 82 Plastic Areas in a Bracket, Shaped by an Oxyacetylene Torch, Etched with Fry's Reagent.

Figure 83 Four Views of a Section of a Bracket Shaped by an Oxyacetylene Torch.

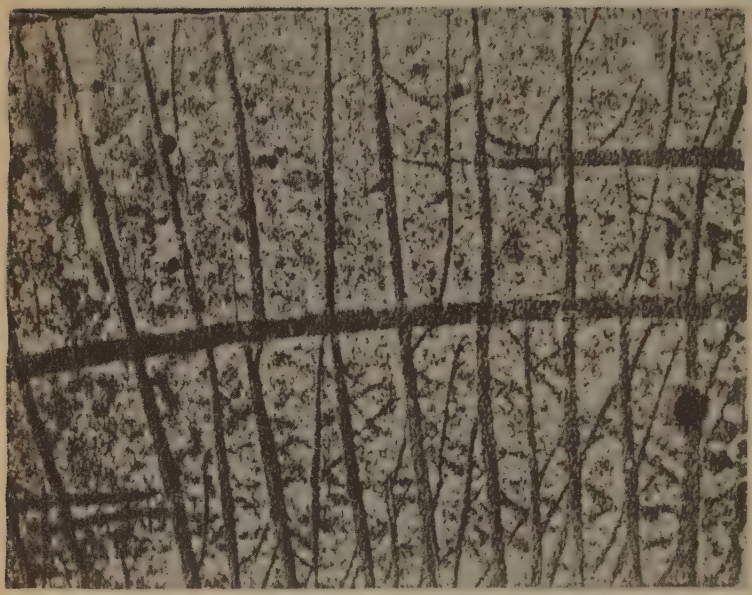

Figure 84 Plastic Areas in a Bracket Shaped by an Oxyacetylene Torch.

3. Microscopic examination of the structural brackets failed to show any localized defects.
4. The conclusions derived from the first part of this work proved that normally tough steel cold worked 10 to 20% and then annealed from 150° to 200° C. has its toughness considerably reduced.

GENERAL COMPREHENSIVE DISCUSSION

Most of the previous work on this subject was not sufficiently comprehensive. The chief reason undoubtedly was that each individual worker was interested in only one particular phase of the subject; thus each piece of research was limited. In some cases tensile tests were made, but impact tests were generally ignored; in others, where both tests were performed, they were either incomplete or not enough emphasis was devoted to the correlation of these tests. Again, it was discovered that some investigators made only Izod impact tests, without considering other tests.

In all this confusion, the necessity for a comprehensive study of the effect of cold work followed by annealing at low temperatures became more and more apparent, more especially in order to view the facts in a general sense. In no other way could the results of tensile tests be related to those obtained from bend, hardness and impact tests.

Such a consideration has proven fruitful. The tensile results interpreted in the light of the impact test results have brought out the fact that the static tension tests indicate when a ductile material begins to lose a considerable amount of its toughness. This is supported by impact tests as well as by cold bend tests. Of course, there are unavoidable errors involved in these tests, but the results obtained are sufficiently accurate to warrant the conclusions derived. In fact, if this feature (when the tensile test will show that steel has lost some toughness) was the only positive result which this research had contributed, it would have been well worth while. Thus we see that static testing is related to dynamic testing, which connection is only to be expected. Brittleness is a fundamental property of a material and, regardless of the nature of the test applied, should always be revealed.

Brittleness in low carbon steels has been the subject of many investigators and only recently attention has again been drawn to failures of structural parts from this cause. Edwards in studying

the effect of flame cutting upon the physical properties of structural steels concluded that this treatment did not materially alter the physical properties, especially the toughness. The nominal chemical composition of the steels employed by Edwards[78] was C. 0.22% Mn. app. 0.80%.

Krefeld,** on the other hand, disagreed with Edwards and reached the following conclusions:

> "The impact resistance of structural steel of the grade investigated decreases as a result of plastic strain. While the loss is dependent upon the degree of overstrain, the rate of decrease is greatest for small strains. The impact value is reduced to 22% of its original value when the overstrain is 8%.
>
> "The application of moderate heat to overstrained steel still further decreases the impact resistance. For the grade of structural steel investigated, this further decrease depended upon the degree of strain and heat and amounted to 45% of the impact value of the strained but unheated material when deformed 3.25% and subsequently heated to 250° C. (482° F.). The greatest effect appears to be produced on material moderately deformed i. e., about 3.25%. The heating of strained steel to the temperature of boiling water will affect a decrease in impact value but the maximum effect is limited to a critical range of temperature between 200° to 300° C. . . . When heated above 300° C., smaller losses of impact value result, until at about 450° to 500° C., no decrease is effected by the subsequent heating.
>
> "Drop tests in the nature of 'practical' demonstrations on flame-cut and cold-sawed brackets showed a marked difference in the shock-absorbing ability of the two types. The tests indicated that the flame-cutting operation had resulted in a decrease of impact value of the previously punched bracket of approximately 40%. These tests confirmed the previously determined experimental data."

Krefeld's curves showing the abnormal reduction in impact resistance have been reproduced in Figure 85. In the same graph are also represented the impact resistance curves determined dur-

**Krefeld, W. J. An Investigation of the Failure of Flame-Cut Bracing Brackets. Civil Engineering Testing Laboratories bulletin No. 3, Columbia University, July, 1929.

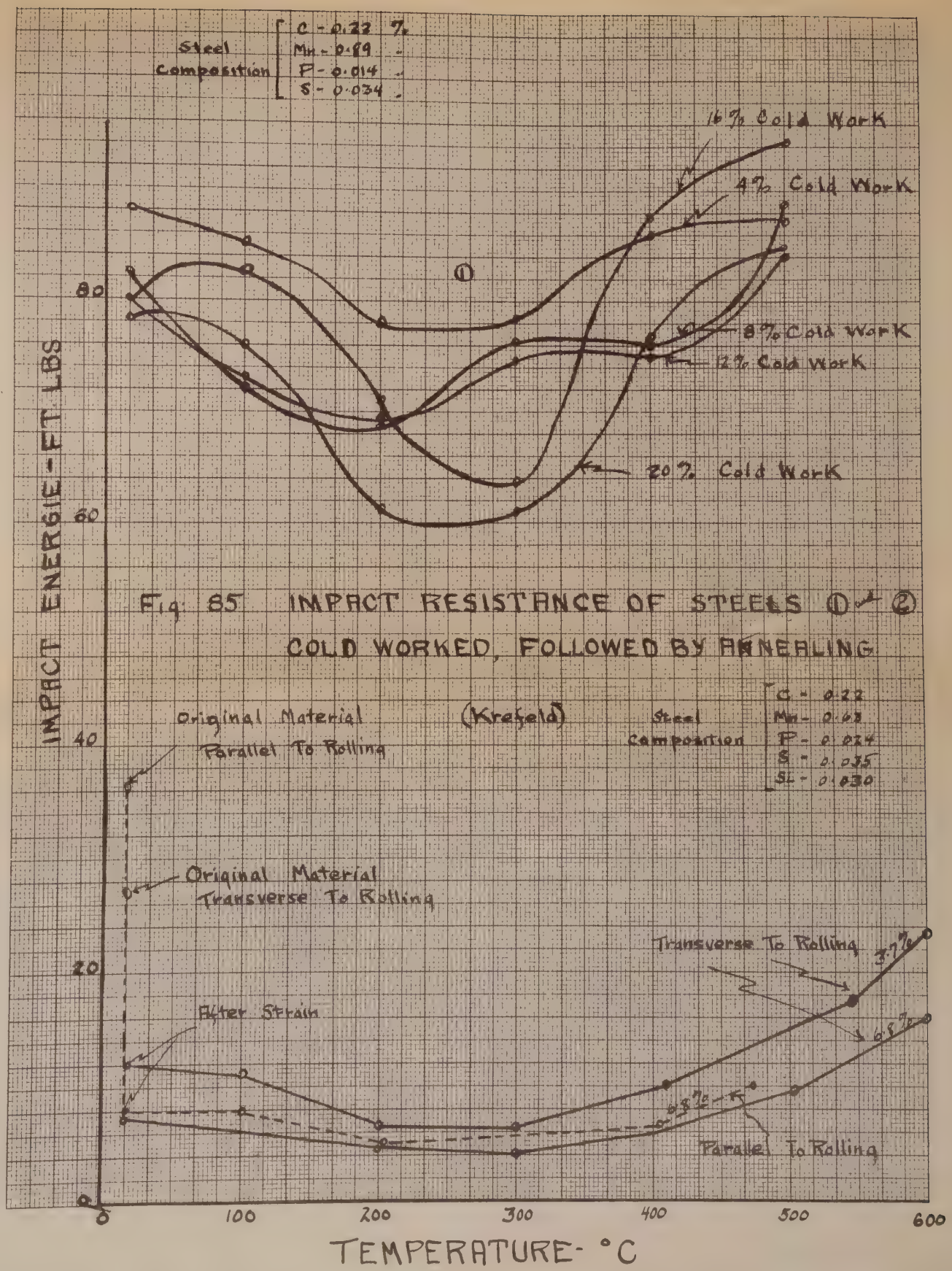

Fig. 85 IMPACT RESISTANCE OF STEELS ① & ② COLD WORKED, FOLLOWED BY ANNEALING

ing the present investigation. It is evident that the lowest impact resistance for the steel used in this study even after cold working it 20%, is greater than the normal value for the steel used by Krefeld. This demonstrates the favorable effects of the addition of slight amounts of manganese, in excess of that usually employed, upon the toughness of low carbon steel. This also explains why Edwards' tests revealed no brittleness for the brackets tested whereas Krefeld showed considerable reduction in impact strength.

†Hoyt, as well as Webster pointed out the strengthening effect of manganese in carbon steel. Webster[82] showed that even in steel as rolled the strengthening effect of manganese is evident. As the manganese content increased from 0.35% to 1.15% and with 0.75% carbon the tensile strength rose from 126,000 to 148,000 lbs. square inch. Moreover, manganese enters both into ferrite and cementite, so that instead of alpha iron and Fe3C, the phases are an alpha solid solution of iron and manganese and a complex iron-manganese carbide. These properties of manganese account for its strengthening effect upon low carbon steel.

Again, by resorting to previous literature on the subject, we find that tension tests on steel cold worked followed by annealing demonstrate the same feature in regard to ultimate strength and yield point. In fact, as already mentioned, Bolsover who also made some impact tests, demonstrated this fact quite clearly. When it was discovered that impact resistance was a minimum at a 250° C. anneal it was also found to be the point at which the ultimate strength and yield point of the tensile tests coincide. Similar relationships are seen also in the work of others.

If only tensile tests were performed, undoubtedly the true interpretation of the importance of the ultimate strength and yield point, as affected by cold work prior to low temperature anneal, would have been overlooked. It was only when such results were studied in connection with bend, impact, and hardness testing, that its full significance was obtained.

Final General Conclusions

The composite diagrams make it possible to find the physical properties of the steel treated under various conditions. As a consequence of the experiments performed, the following conclusions have been reached.

†Hoyt, S. L. Metallography, Part 2, The Metals and Common Alloys. 1921, McGraw-Hill Book Co., Inc.

1. The physical properties of cold worked steel are altered by annealing at low temperatures.

2. The ultimate strength, as well as the yield point is raised, the former attaining its maximum value on annealing at 300° C., while the latter requires annealing at 200° C. to attain its highest value.

3. 0.22% C.-0.89% Mn. steel cold worked from 12 to 20% followed by annealing from about 150 to 250° C. will have its toughness lowered approximately 23%. The notch bar toughness of this steel is relatively high when compared with the usual grade of structural mild steel (with lower manganese contents).

4. The hardness of such steel cold worked from 0 to 20% can be increased by low temperature annealing from 200 to 400° C. However, a smaller percentage increase in hardness is to be expected by annealing such steel cold worked from 10 to 20% than from steel cold worked from 0 to 10%.

5. In all cases the hardness of such steels, regardless of the amount of cold work (0 to 20%) will be lowered on annealing above 500° C.

6. Bend and impact notched bar tests prove that the usual toughness of cold worked steel is reduced on annealing at temperatures below 300° C. The critical annealing temperature ranges varied; steel cold worked from 0 to approximately 10% showed the greatest lowering within the temperature range of 150 to 250° C., whereas when this steel was cold worked from 10 to 20%, the corresponding critical annealing temperature range was from 150 to 300° C. In all cases the minimum toughness was found either after a 200° C. or 250° C. anneal.

7. Whenever the ultimate strength and yield point of normally tough steels are so altered that they practically coincide, the toughness of such steels reaches its minimum value.

8. Structural steel, such as is used in structural I-beams, which normally has a low impact value, should be treated with caution when cold working is followed by flame cutting.

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